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ZONAL PRECIPITATION OF ORES FROM A MIXED SOLUTION.

MANJIRÔ WATANABÉ.

THE PHENOMENON OF DIFFERENTIAL PRECIPITATION.[1]

THE phenomenon of zonal or differential precipitation from a mixed solution has an important bearing on the genesis of certain textures of ores. Since, however, it has not been described by investigators, a brief account of the phenomenon will be given in this paper.

My study was begun with an experiment: About 2.5 cc. of a gelatin jelly, which contained in solution a small amount of sodium sulphide, was poured in a small glass tube, closed at the lower end. The jelly filled the lower half of the tube, held vertical, and soon consolidated. Then a mixed solution of copper and zinc sulphates was poured on the jelly in the tube. The deposition of both zinc and copper sulphides commenced immediately as the metallic salts diffused from the overlying solution into the jelly containing sodium sulphide. The precipitation of the two sulphides, however, did not occur in a mixture, but in two different zones, sharply separated from each other. Both zones advanced with time deeper into the jelly, still retaining a sharp boundary between them. The zone of white colloidal zinc sulphide[2] always advanced deeper than that of dark brown

[1] The detailed account of the phenomenon will be given in Sci. Rept. Tôhoku Imp. Univ., Ser. III., Vol. I., Nos. 1–2, which will soon appear.

[2] Colloidal precipitate of zinc sulphide is white in color. Such a precipitate is found also in nature. For instance, large cavities in workings of Galena, Kansas,

copper sulphide, the former being replaced from its rearward side by the latter, while it was advancing deeper on its forward side.

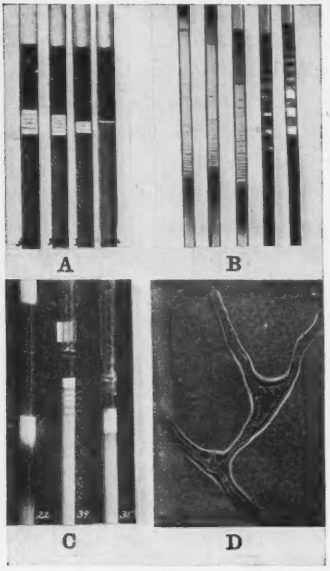
In other experiments, the relative concentration of zinc and copper sulphates in the diffusing solution was changed from Cu 95 : Zn 5 to Cu 5 : Zn 95. In any case, the zone of zinc sulphide advanced at the front of the zone of copper sulphide. The order of these two zones was always constant independent of the relative concentration of diffusing salts in the overlying solution. (Fig. 58, *A*.)

Similarly, when a jelly containing sodium sulphide was overlain with a mixed solution of ferric sulphate and zinc sulphate, colloidal precipitates of white zinc sulphide and black iron sulphide advanced in successive zones into the jelly. The zone of iron sulphide advanced deeper than that of zinc sulphide in any concentration relations between the diffusing sulphates. In this case, however, separation of the two sulphides was not complete, the mode of mixture being different according to the relative concentration of the two salts. When the diffusing solution contained much zinc and less iron, a small amount of iron sulphide remained for a certain period in the zinc sulphide zone, giving it a grayish appearance. Whereas, when the diffusing solution contained more iron than zinc, a few rhythmic layers of zinc sulphide appeared in the zone of iron sulphide, which advanced at the front of the main zone of zinc sulphide. Still the boundary between the two main zones was clear. (Fig. 58, *B*.)

When the jelly containing some alkali was overlain with a mixed solution of ferric and copper nitrates, two successive zones of iron and copper hydroxide were formed, the copper compound always forming the forward zone in any concentration relation between the two diffusing salts.

Another interesting result was observed when the experiment was made on a glass plate instead of a small tube. For instance, a layer of gelatin jelly containing a small amount of sodium

have been found filled with a white precipitate, which consisted of nearly pure zinc sulphide with acid water. (*Am. Journ. Sci.*, Ser. III., Vol. 40, 1890, p. 168.)



EXPLANATION OF FIG. 58.

A. Zonal precipitation of zinc sulphide (white) and copper sulphide (black) in sodium sulphide-bearing jellies due to the diffusion of mixed solutions of zinc and copper sulphates in various relative concentrations. (½ natural size.)

B. Precipitation of zinc sulphide (white) and iron sulphide (black) in different zones in jellies containing sodium sulphide due to the diffusion of mixed solutions of iron and zinc sulphates. Each zone consists of rhythmic layers of precipitate. The uppermost dark colored zone consists of ferric hydroxide, produced by hydrolytic dissociation of ferric sulphate. (½ natural size.)

C. Precipitation of various metallic sulphides from mixed solutions of corresponding sulphates in artificial clays containing sodium sulphide. (½ natural size.)

D. Zonal precipitation of zinc carbonate (white outer zone), copper carbonate (dark colored intermediate zone) and iron hydroxide (central dotted portion) from a mixed solution of sulphates of these metals in a gelatin layer containing sodium carbonate. (½ natural size.)

carbonate was spread on a glass plate, and a mixed solution of sulphates of copper, zinc and iron was added on the layer along lines which resembled in shape certain fissures in ores. As the result of diffusion from the mixed solution, zinc carbonate, copper carbonate and iron hydroxide appeared in successive narrow zones on both sides of the lines, along which the solution was added. In any concentration relations, the zinc carbonate, thus produced, formed the external zone and the iron compound made the innermost zone, the copper carbonate forming the intermediate zone. The whole appearance was similar to certain parallel zones of minerals, which border the fissures of some ores. (Fig. 58, *D.*) Similarly, when a mixed solution of copper and iron sulphides was added on a layer, made of a pasty mixture of kaolin, water and calcium carbonate powder, the precipitate of copper carbonate always formed the external zone along the front margin of diffusion, while the iron compound made the internal zone nearer to the source of diffusion. Thus the phenomenon was observed not only in gelatin jellies but also in artificial clays without gelatin. (Fig. 58, *C.*)

Diffusion is not a necessary factor for producing this result. The same phenomenon was observed when the mixed solution penetrated the reacting medium through capillary movement. This was ascertained when a mixed solution of copper and iron sulphates ascended the dried mass of calcium carbonate powder, which adhered on the inner wall of the tube, used for the experiment of diffusion.

THE ORDER OF SUCCESSIVE ZONES.

As far as I have experienced, the following order of succession was observed in the advance of precipitates, which were formed by the penetration of a mixed solution into a medium containing a reacting substance.

(Rearward or Internal Zone.)	(Intermediate Zone.)	(Forward or External) Zone.
Copper sulphide	.....	Zinc sulphide.
Copper sulphide	.....	Iron sulphide.
Zinc sulphide	.....	Iron sulphide.
Copper sulphide	Zinc sulphide	Iron sulphide.
Copper sulphide	Zinc sulphide	Manganese sulphide.
Iron hydroxide	.....	Copper hydroxide.
Iron hydroxide	.....	Copper hydroxide.
Iron hydroxide	Copper carbonate	Zinc carbonate.

THE CAUSE OF DIFFERENTIAL PRECIPITATION.

The remarkable phenomenon, that the order of advance of precipitation of two or more compounds from a mixed solution is independent of the relative concentration of the diffusing substances in the solution, will be explained by assuming the order of stability of the precipitates against the diffusing mixed solution. As for example, when zinc sulphide and copper sulphide are formed by the diffusion of a mixed solution of copper and zinc sulphates, zinc sulphide is not stable in this mixed solution, while copper sulphide is stable. According to Zies, Allen, and Merwin,[3] zinc sulphide is easily converted into copper sulphide by the reaction:

$$ZnS + CuSo_4 \rightarrow ZnSO_4$$

but this reaction is not reversible under usual conditions. Accordingly, zinc sulphide can not remain deposited in the presence of a mixed solution of copper and zinc sulphates. If it be once formed, the copper sulphide in the solution changes it into copper sulphide and zinc sulphate. The latter product, being soluble in the water of the diffusion medium, advances farther into a zone where no copper sulphate has yet arrived in excess and is deposited only in such a zone; whereas, copper sulphide remains stable in the zone where both sulphates exist in excess. This is the reason that zinc sulphide is formed always in a zone farther than that of copper sulphide from the source of diffusion. Similarly when iron hydroxide and copper carbonate are deposited by the penetration of a mixed solution of copper and iron sulphates

[3] E. G. Zies, E. T. Allen and H. E. Merwin, ECON. GEOL., Vol. 11, 1916, pp. 407–503.

in a clayey mass containing calcium carbonate, copper carbonate can not remain in a zone where iron sulphate is found in excess. Accordingly, the copper diffuses farther into a zone where the ferric salt has not arrived in excess. Thus the zone of copper carbonate always advances farther than that of ferric hydroxide.

GEOLOGICAL MEANINGS OF DIFFERENTIAL PRECIPITATION.

In any case described above, different compounds are precipitated in successive layers, all at the same time. This suggests a new explanation for the genesis of certain successive zones of minerals, which are developed along both sides of fissures. These zones have been supposed to have appeared in successive periods. For instance, if a fissure is bordered by successive zones of malachite and limonite, the mineral forming the inner zone traverses in appearance that of the outer zone. Therefore, it has been usually believed in such cases that the external zone was formed earlier than the inner zone. This may be true in many cases, but not necessarily. Such a texture may easily be formed contemporaneously, as is shown by experiments described above.

The successive layers of malachite and limonite which often surround blocks of limestone in the oxidized zone of ore deposits may be similarly explained by assuming a reaction of mixed sulphate solutions on the limestone. A good example is given by Lindgren, Graton and Gordon [4] from the Apache districts, New Mexico, and is quoted by Emmons [5] as an example of banding due to weathering.

The formation of successive mineral zones may occur on a larger scale. When a sulphide deposit, containing zinc, iron and lead, is oxidized, sulphate solutions of these metals will be generated. If such a mixed solution penetrates limestone, the reaction products will appear in successive zones on a large scale. As lead sulphate is least soluble in sulphate solutions, it remains

[4] W. Lindgren, L. C. Graton and G. H. Gordon, U. S. Geol. Surv., Prof. Pap., No. 68, 1910.

[5] W. H. Emmons, "The Principles of Economic Geology," N. Y., 1918, p. 225.

mainly in the place of oxidation. Zinc and iron sulphates in solution react on limestone and produce zinc carbonate and iron hydroxide. As the former is more stable than the latter in mixed solutions of zinc and iron sulphates, iron hydroxide is deposited in limestone nearest to the place of oxidation, while zinc carbonate is deposited in a zone farther from the source of the sulphate solution. The order of precipitation is well exemplified in the oxidation zones of Leadville, Colo., described by Loughlin.[6] It may be expected that a zone of zinc carbonate will be found beyond the zone of limonite in such a type of deposit.

[6] G. F. Loughlin, U. S. Geol. Surv., Bull. 681, 1918.

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ANGULAR INCLUSIONS AND REPLACEMENT DEPOSITS.[1]

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Introduction.

Does an angular inclusion surrounded by a foot or so of ore indicate that the ore deposit could not have been formed by the process of replacement? How is the presence of such an angular fragment to be explained, and what does it signify with respect to ore-forming processes? The angular nature of the fragment is the feature to which I wish to direct attention. Commonly it is said that the angularity of an isolated fragment precludes the probability of replacement having operated, and this is the topic that will be discussed in this paper. The broader problem of the origin of angular fragments in ore deposits, particularly veins, for some time has aroused the curiosity of geologists, and diverse ideas are held to account for them, the latest being that advanced by Spurr.[2] But this paper will deal only with angular fragments insofar as they may be considered to oppose or support a replacement origin for the deposits that inclose them. It is my belief that incomplete replacement by ore will leave residual nuclei with angular as well as with rounded outlines, and that the presence of angular fragments does not imply that replacement has played no part in the formation of the deposit.

PRESENT IDEAS.

From the time of the earliest descriptions of ore deposits rounded or angular fragments in the midst of ore have been commented on. They were noted mostly in veins but their presence in irregularly shaped ore bodies was also pointed out. Ever

[1] Society of Economic Geologists, New York Meeting, May, 1924.
[2] "The Ore Magmas," McGraw-Hill, 1923, Chaps. 2, 15, 18.

since replacement ore bodies became recognized, isolated fragments of wall rock imbedded in the midst of ore have commonly been regarded as highly characteristic of the type. But it has further been supposed that the fragments to be diagnostic of replacement deposits must be rounded—a form that results by the mineralizing solutions attacking, first of all, the protuberances of the fragment.

This idea was in the mind of Becker[3] as far back as 1888 for he states "Had an active process of replacement gone on, one would expect to find angular masses of ore containing rounded kernels of rock." Again he states "In case of a real replacement the rock replaced will be represented in the resulting ore bodies only by residual kernels."[4] At a later date Lindgren in his classic paper[5] on the "Metasomatic Processes in Fissure Veins" stated under the "Criteria of Metasomatism" that "the occurrence of remaining nuclei of unaltered rock is sometimes an available criterion; but it must be used with caution . . . on account of its similarity to actual inclusions of country rock in vein-filling. If the alteration proceeds normally from the outside of a crystal or angular mass of rock, the tendency will be toward rounded residual portions in the interior of the mass." Also Irving in his paper on the "Replacement Ore Bodies and Criteria for their Recognition" says[6] "the unreplaced core is bounded by a wavy, rounded line of demarkation" and his Figs. 103 and 106 show such rounded residual cores. Still later, W. H. Emmons states[7] "the original unaltered or slightly altered material will remain as nodules or irregular bodies . . . many irregularities or sharp protuberances are generally attacked first because they present greater surfaces to the decomposing solutions. The ores of unaltered original substances may become smaller and smaller until the new substance completely replaces them." Further, in refer-

[3] U. S. Geol. Surv. Mon. 13, 1888, p. 395.
[4] *Idem*, p. 398.
[5] *Trans. Amer. Inst. Min. Engrs.*, vol. 30, p. 596, 1900.
[6] ECON. GEOL., vol. 6, p. 644.
[7] "Principles of Economic Geology," McGraw-Hill, 1918, p. 218.

ence to fragments, Emmons also says [8] "On the other hand, fragments included in replacement deposits may be rounded somewhat by solution, especially on their edges that are most exposed."

Many other examples might be cited but the above quotations illustrate the prevalent thought that isolated fragments, if rounded, are a criterion of replacement deposits. With this conclusion I am in hearty agreement. However, the *converse* of the argument—that angular fragments are a proof that replacement has not taken place—I am not willing to admit. And this idea is widely advanced to distinguish other types of deposits (cavity-fillings chiefly, also vein-dikes) from replacement deposits. As an argument opposed to replacement deposits, it is almost as commonly met with in the literature as is the argument of rounded fragments in favor of replacement. Most frequently, and rightly, angular fragments are interpreted as an indication of vein fillings; most students of ore deposits will recall instances of brecciated openings cemented by vein matter, not susceptible of any other interpretation than that of filling. But in such instances the fragments are not unsupported, excepting possibly a separation each from the other, by thin crusts of vein stuff.

However, the argument that angular fragments indicate vein filling as opposed to replacement is not always restricted to plainly crustified deposits which have been shown so clearly by Posepny [9] to be proof of an origin by cavity filling from circulating heated waters. For instance, Bergeat and Stelzner,[10] Phillips and Louis,[11] DeLaunay,[12] and others indicate that angular fragments denote a process of cavity-filling. The same idea is also given recently by Rastall,[13] and Irving [14] warns his reader that "angular inclusions suggest cavity fillings." The same idea is even more

[8] *Idem*, p. 227.

[9] *Trans. Amer. Inst. Min. Engrs.*, vol. 23, 1893, p. 197.

[10] "Die Erzlagerstätten," Leipzig, 1906, vol. 2, pp. 524, 536, 1013.

[11] "A Treatise on Ore Deposits," London, p. 91.

[12] "Gîtes Minéraux et Métalliféres," Paris et Liége, 1913, vol. 1, p. 153.

[13] "The Geology of the Metalliferous Deposits," Cambridge Univ. Press, 1923, p. 101.

[14] *Loc. cit.*, p. 654.

clearly brought out by Emmons,[15] who presents side by side two figures,[16] one portraying vein matter containing isolated *rounded* inclusions to illustrate replacement, and the other with unsupported *angular* fragments to portray vein-filling.[17] Spurr had this clearly in mind when he wrote[18] "two circumstances show that . . . the veins occupied open fissures and were not by any chance formed by replacement. First, they contain angular fragments of wall rocks which are neither rounded, corroded, nor replaced. . . ." Again in reference to the veins of Cobalt, Ontario, he states[19] "if these fragments of diabase in the vein are residuals from a replacement process, how shall we explain the sharp outlines, and above all the long sharp angular corners?" On another page[20] he says "included angular fragments show the lack of any appreciable amount of surplus *aqueous* or *gaseous components,* such as would have been expected on the consolidation of an aqueous quartz magma. No essential part of the quartz is due to replacement."[21]

ANOTHER VIEWPOINT.

The writer appreciates that angular fragments included in ore deposits have been brought there by different causes and denote different processes of ore deposition. He recognizes that unsupported corroded fragments are valuable criteria of replacement deposits, particularly if structure lines of the fragments, such as bedding or schistosity, are parallel with similar structure lines of

[15] *Loc. cit.,* p. 223.

[16] In the first impression of Emmon's book the titles for these two figures on page 223 are transposed.

[17] The rounded and angular fragments of these figures are not meant to be the sole criteria of replacement and filling respectively, for in the former structure lines show that the fragments have not moved, whereas in the latter they have been rotated.

[18] *Loc. cit.,* p. 129.

[19] *Idem,* p. 135.

[20] *Idem,* pp. 687–688.

[21] This paper is not intended as a discussion of Mr. Spurr's idea of angular fragments as a criterion of vein dikes, but relates only to one phase of it—the assumption that angular fragments are not to be found as residual nuclei in replacement deposits.

the wall rocks. He also recognizes that included angular fragments may have been caused by brecciation or comminution of wall rocks and later cementation by vein filling. He further appreciates without commitment the strength of the argument set forth by Mr. Spurr [22] to explain the kind of included fragments vividly pictured by him. But he also thinks that suspended angular fragments may under certain conditions remain as residuals in replacement deposits. From this, it follows that suspended angular fragments cannot always by used to exclude the process of replacement in the formation of ore bodies, as in the citations previously mentioned. The evidence for this conclusion is scanty but suggestive, and it is hoped that more data may be forthcoming by other observers to help prove or disprove it. The evidence may by considered under four headings: 1, microscopic; 2, hand specimens; 3, field; and 4, literature.

THE EVIDENCE.

The observance in several mining districts of angular fragments included within unmistakable replacement deposits aroused the writer's curiosity as to their significance. He had always previously considered that if the deposits had been formed by replacement the inclusions should have their corners rounded by the solutions that produced replacement of rock by ore. Also, in the microscopic study of polished ore specimens, instances were noted repeatedly of angular as well as rounded residuals in cases where one mineral had replaced another. The observation was checked whenever opportunity arose and mineral deposits and hand specimens were scrutinized carefully to see what evidence they might yield. As conviction grew that angular as well as rounded fragments may remain as unsupported residuals, instances were looked for in the literature.

Microscopic Evidence.—Those who have observed polished specimens with the reflecting microscope are familiar with the phenomena of replacement of one sulphide by another. It may be seen where later primary (hypogene) minerals replace earlier

[22] "The Ore Magmas," Chaps. *2*, *15*, and *18*.

primary (hypogene) minerals, or more commonly, in the case of secondary (supergene) sulphide replacement. Where replacement has been incomplete, as is usually the case, residual nuclei of the mineral being replaced will remain. These commonly are rounded but not infrequently are angular. The angularity is most evident in the first stages of replacement and results largely from replacement proceeding outward from intersecting veinlets. By way of illustration, chalcopyrite may be undergoing replacement by chalcocite. The alteration may proceed around the margins of an individual chalcopyrite area or, as is more commonly the case, from intersecting veinlets that traverse the chalcopyrite. Such intersecting veinlets usually inclose angular areas of chalcopyrite, and the growth of the chalcocite at the expense of the chalcopyrite may proceed parallel to the walls of the intersecting veinlets, so that the dwindling nucleus of chalcopyrite remains angular. These stages are pictured diagrammatically in Fig. 59. Such angular residuals are matters of everyday observa-

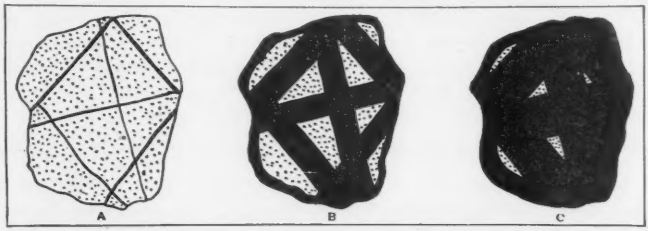

FIG. 59. Diagram to illustrate formation of angular inclusions by replacement proceeding outward from intersecting veinlets. *A*, veinlets of mineral (black) cutting ore or rock (stippled); *B* and *C*, more advanced stages.

tion, and the writer has noted scores of them. An example from Morenci, Ariz., is shown in Fig. 60. Similar illustrations are also pictured by many investigators. For instance, Lindgren shows pyrite from Clifton, Arizona, altering to chalcocite which contains angular inclusions of pyrite,[23] and on another page[24] shows

[23] "Mineral Deposits," 1919, p. 852.

[24] *Idem*, p. 875.

angular fragments and spicules of residual galena in anglesite; Rogers presents an excellent photomicrograph [25] in which sharp angular fragments of pyrite are contained in the bornite that is replacing it; equally good photomicrographs are shown by Bonillas, Tenney, and Feuchère [26] of Bisbee, Ariz., ores with angular

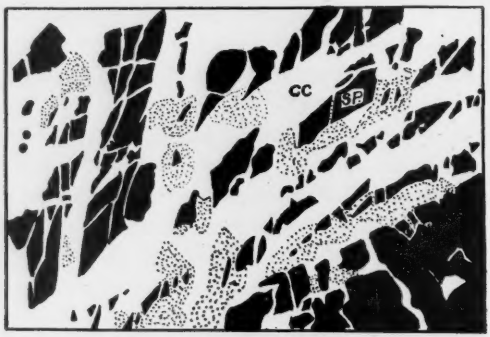

FIG. 60. Camera lucida drawing of polished surface of supergene enriched ore from Morenci, Arizona. Chalcocite (white) replacing sphalerite (black), leaving angular residuals. Stippled areas are ghost-like remnants of incompletely replaced sphalerite. × 40.

fragments of pyrite inclosed in replacing sulphides; Means pictures pyrite replacing and including angular quartz fragments from Red Cliff, Colorado; [27] and Ransome by a camera lucida drawing shows angular quartzite fragments in replacing cinnabar from Almaden, Spain.

It is unnecessary to draw upon further illustrations, for the ones mentioned above demonstrate that angular inclusion may result from the replacement of one mineral by another. And the evidence revealed by the microscope on a small scale is similar to that which may be seen on a large scale in hand specimens or in the field.

[25] ECON. GEOL., vol. 11, plate 17, p. 370, 1916.
[26] *Trans. Amer. Inst. Min. Engrs.*, vol. LV., 1916, p. 334.
[27] ECON. GEOL., vol. 10, 1915, plate 1, Fig. 36, p. 14.

Evidence from Hand Specimens.—Hand specimens in the Laboratory of Economic Geology of Yale University, of known location in deposits that are considered by those who have studied them to have been formed by replacement, were scrutinized carefully and some were broken open to see the character of the inclusions they might contain. The search revealed many specimens containing rounded fragments, and some with angular inclusions; the latter from Leadville, Colorado; Bisbee, Arizona; Black Hills; South Dakota; and the Highland Boy Mine at Bingham, Utah.[28] Still other specimens were noted with angular fragments that could not with certainty be determined as inclusions. One of the specimens from the white limestone stope of the Tucson Mine, Leadville, Colorado, is pictured in Fig. 61. The unsupported angular fragments in the other specimens are similar to those shown in Fig. 61.

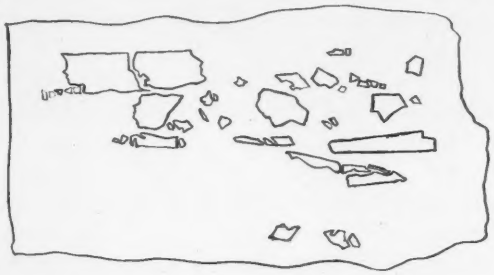

FIG. 61. Tracing obtained by placing oiled tracing paper over polished slab of ore from Tucson Mine, Leadville, Colorado. Isolated inclusions of white limestone surrounded by admixed pyrite, sphalerite, and galena. Reduced to ¼ size.

[28] For the discussion of the replacement origin of these deposits see respectively: The Downtown district of Leadville, Colo., by J. D. Irving and S. F. Emmons, U. S. G. S. Bull. 320, 1907; Geology of the Warren mining district by Y. S. Bonillas, J. B. Tenney, L. Feuchere, T. A. I. M. E. vol. 55, 1917, pp. 284–355, and F. L. Ransome, U. S. G. S. Prof. Paper 21, 1904; Economic resources of Northern Black Hills by J. D. Irving and S. F. Emmons, U. S. G. S. Prof. Paper 26, 1904; Bingham Mining district by J. M. Boutwell, U. S. G. S. Prof. Paper 38, 1905.

Field Evidence.—Included angular fragments similar to those described in hand specimens have also been observed on a larger scale in the field. For example, at Kennecott, Alaska, in a deposit studied in detail by the writer, are large irregularly shaped bodies of massive chalcocite that occupy parts of certain limestone beds and for which a replacement origin has been argued at length elsewhere.[29] Within the chalcocite have been observed several instances of unsupported angular remnants of limestone that vary in size from an inch to several feet in diameter. These inclusions differ in no observable respect from the limestone that incloses the ore bodies and represent simply residual nuclei of incomplete replacement.

One instance is impressed clearly on my mind of a sheeted zone that crossed a limestone bed and which contained several parallel but knobby bands of chalcocite. The stope showed 13 feet of ore and about 9 feet of this was solid chalcocite. The wavy walls of each band of chalcocite were clean and sharp against the alternating limestone bands. In the limestone bed immediately beneath the ore there was a continuation of the sheeted zone, free of ore, that showed the spacing of the fractures. Where the fractures of the sheeted zone were closely spaced, wider bands of almost solid chalcocite resulted; where they were more distant, narrower bands of chalcocite occurred. Between some of the narrower bands were angular plates of unreplaced limestone, each unconnected with the other. I picked down some of them and found they were entirely surrounded by chalcocite. They were angular inclusions in a replacement ore body. Some still narrower bands of chalcocite were separated by wider bands of limestone traversed by veinlets of chalcocite that broke the continuity of the limestone band. Had replacement proceeded further, there would have been left angular rock inclusions bounded by the flanking chalcocite bands, and by the cross-cutting jagged veinlets. The angular residuals above mentioned are considered to have been so formed and in the closely

[29] Bateman, A. M., McLaughlin, D. H., "Geology of the Ore Deposits of Kennecott, Alaska," ECON. GEOL., vol. 15, 1920, Fig. 9, p. 32.

spaced sheeting, replacement from each small fracture coalesced with the adjoining one to form the wide bands of chalcocite, containing only an occasional rock residual. In all the instances observed of angular fragments in the Kennecott deposits, the angular form was caused by the incomplete coalescence of ore replacement outward from fractures.

FIG. 62. Reproduction of notebook sketch of drift face, Bonanza Mine, Kennecott, Alaska. Replacement vein of chalcocite in limestone with some angular inclusions.

A notebook sketch of one such smaller occurrence is shown in Fig. 62. Another occurrence was noted by the writer on Hudson Bay Mt., British Columbia, where massive pyrrhotite replaces altered andesite and rhyolite. Unreplaced angular inclusions a few inches in diameter are entirely surrounded by pyrrhotite. Still other occurrences that depict similar features were sketched by the writer at Leadville, Colorado, Bingham, Utah, and near Ely, Nevada.

Dr. F. L. Stillwell, of Bendigo, Australia, showed me several photographs of the Bendigo quartz deposits in which were angular inclusions of wall rock surrounded by quartz that contained, nearby, ghost-like outlines of other fragments that had been completely replaced by quartz. Also Dr. Ernest Howe showed me specimens and photographs obtained by him at the North Star

Mine in Grass Valley, California, that display angular inclusions of granodiorite in the midst of white quartz—the same quartz also containing faint outlines of other digested rock fragments which in these particular cases he considers were replaced by quartz.[29a]

Evidence from the Literature.—In addition to the writer's own observations, the broader experience of other workers as expressed in the literature, lends support to the theme of this brief paper. Such support is commonly not to be found in direct, or even indirect, statements, but rather in the illustrations that accompany the articles—illustrations presented mostly for other purposes. In two or three cases, angular fragments in replacement deposits have been commented upon as, for example, by Lindgren,[30] who, after pointing out the tendency of replacement residuals to be rounded, says "The replacement of crystals or angular fragments may occur without changing in the least, even by the rounding of corners, the form of the masses." Also Emmons, after pointing out the distinction between angular fragments included in fissure fillings and the rounded ones of replacement deposits, says:[31] "In a small deposit in Elko County, Nevada, unaltered angular fragments of limestone are inclosed in a large body of quartz that had been deposited principally by the replacement of the limestone." Again, Ransome in his work[32] on the "Copper Deposits of Ray and Miami, Arizona," in reference to the replacement of pyrite by chalcocite says: "As a rule the residual grains of pyrite, even if much reduced in size, retain to a surprising degree their original form and angularity." Other such comments probably exist but have escaped my notice.

Another form of evidence from the literature is to be found in illustrations that show angular inclusions of minerals or rock surrounded by vein matter that is considered to have resulted from replacement. Such evidence, however, is to be accepted

[29a] These inclusions and arguments for a replacement origin are to be described by Dr. Howe in a manuscript in preparation.

[30] *Loc. cit.*

[31] *Loc. cit.*, p. 227.

[32] U. S. Geol. Surv. Prof. Paper 115, 1919, p. 162.

with caution for the illustrations were not presented by the authors for the particular points which the present writer is taking the liberty of deducing from them. In some cases there may be other explanations, not given in the articles, to explain the presence of the angular inclusions. But if cases of doubt be excluded, there still remain plenty of examples where the accompanying descriptions leave little doubt in the mind of the reader as to the replacement origin of the material pictured.

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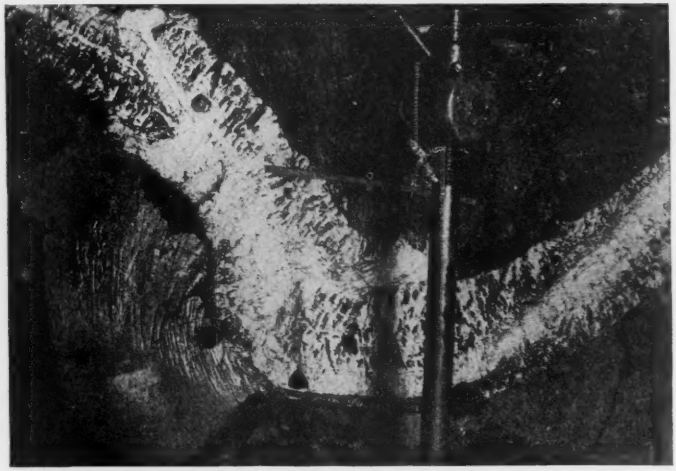


FIG. 63. Spur in slate simulating saddle reefs but crossing bedding planes. Angular inclusions in quartz considered by Stillwell to be replacement quartz. (From Stillwell, ECON. GEOL., vol. 16, p. 154, 1921.)

An illustration (here reproduced as Fig. 63), presented by Stillwell [33] to support his argument of replacement origin for the Bendigo quartz lodes of Australia, shows innumerable angular fragments of country rock which he implies are residuals. In addition there are included in the quartz, carbonaceous "residues from replaced country rock." Another illustration of dissemi-

[33] ECON. GEOL., vol. 16, 1921, Fig. 17, p. 154.

nated galena replacing limestone in which are jagged inclusions is shown by Buckley.[34] Lindgren also in his "Metasomatic Processes in Fissure Veins" presents a photograph[35] showing galena ore from the Bunker Hill and Sullivan Mine, Coeur d'Alene, Idaho, that replaces quartzites and contains angular inclusions of the wall rock. Excellent photographs of schist ore with veinlets of pyrite partly replaced by chalcocite that contains apparently isolated angular particles of pyrite, from the Inspira-

FIG. 64. Smaltite and white calcite in diabase and containing angular inclusions of diabase, O'Brien Mine, Cobalt, Ontario. Believed by Whitehead to be replacement vein. (From Whitehead, ECON. GEOL., vol. 15, p. 116, 1920.)

tion and Ray Mines, Arizona, are pictured by Ransome.[36] Boutwell[37] also shows chalcopyrite and pyrite that has replaced quartz in which angular corners of quartz project into the sulphides and angular fragments are surrounded by sulphides. Another, but less certain case in which the evidence for replacement is not without dispute, may be found in an article by Whitehead who argues with vigor for a replacement origin of some of the Cobalt

[34] Missouri Bur. of Geol. and Mines, vol. IX., Part 1, p. 213.
[35] *Loc. cit.*, p. 561.
[36] *Loc. cit.*, Plate 54, p. 163.
[37] U. S. Geol. Surv. Prof. Paper 38, 1908, Plate 35, p. 198.

veins,[38] and points out particularly that numerous included fragments are not only unsupported but angular. His Plate VII., *a*, here reproduced as Fig. 64, illustrates this angularity. Whitehead's conclusion of replacement is not unchallenged, however, for Spurr [39] remarks that a study of this photograph does not give much faith in a replacement explanation and holds (as previously quoted) that the angularity of the fragments excludes replacement. Spurr goes even further and uses these same angular fragments as support for his idea "that the intrusive vein magma which split open the rock and forced its way in was heavy enough, or viscous enough, or congealed quickly enough, to hold these diabase fragments in suspension." Two opposing inferences are thus drawn from the same evidence and our reader may take his choice. If the ore was formed by replacement, the photograph is an excellent example of angular nuclei.

WHY ARE NUCLEI ANGULAR?

When a rock fragment is attacked by solutions, projecting corners are the first to succumb and gradually a rounded outline is produced. An example familiar to all geologists is the rounding of soluble materials by surface waters. It is logical to expect that rock fragments undergoing replacement by ore would also be rounded. And accumulated observations of replacement deposits record that rounded inclusions are characteristic.

A rounded outline should normally be expected when the material being replaced is porous or when the attack by solutions on a fragment is peripheral. Therefore, fragments once isolated should, by continued peripheral attack where opportunity is afforded for all sides of the fragment to be dissolved uniformly, have rounded outlines. *A priori* reasoning leads one to the conclusion that in an advanced stage of replacement by ore, nuclei should nearly always be rounded.

But how, then, are angular inclusions resulting from ore replacement to be explained? In most cases, I think, angular in-

[38] ECON. GEOL., vol. 15, 1920, pp. 120–124; 116, Plate VII.
[39] "The Ore Magmas," vol. 1, p. 135.

clusions arise from the replacement outward from intersecting fractures, as in Fig. 59, rather than from peripheral replacement, and typify the earlier stages of the process of replacement. This may be seen best on polished surfaces of ores when examined with the reflecting microscope. The same condition may be observed on a larger scale, as in the case of the Kennecott deposit sketched in Fig. 62. And many replacement deposits, particularly replacement veins, originate by the progressive metallization of the walls of small and intersecting or branching fractures. By just such a process the isolation of most fragments in replacement deposits is accomplished. In the case of shattered zones subjected to replacement by ore, the fractures afford easy channelways for the replacing solutions and the cessation of metallization in an early stage of replacement should leave many angular rock fragments surrounded by ore. If the inclusions be free from fractures it would be expected that continued replacement of them by ore would be peripheral, and hence the fragments would become rounded.

CONCLUSIONS.

The evidence drawn on above, though by no means all that exists, is sufficient to illustrate without further burden to the reader that angular fragments exist as inclusions—and unsupported ones—in deposits that are considered to have been formed by replacement. Consequently, angularity of inclusions in itself forms no decisive basis of distinction between replacement deposits and cavity fillings; neither does it preclude a replacement origin for the deposit that contains them.

YALE UNIVERSITY,
NEW HAVEN, CONN.

DISCUSSION.

Mr. Spurr: I am in agreement with Professor Bateman, that angularity of a fragment is no sure test that it is an inclusion in a veindike rather than a residual of replacement. In each case the evidence must be studied carefully, and every point taken into consideration. The

three points referred to by Professor Bateman in his quotation from my book, that in the specific case referred to the fragments were "neither rounded, corroded or replaced," form a better picture of the tests which must be applied in determining a real inclusion in a veindike than the single one of angularity; although there is no formula of any kind that can be universally relied upon. Such included fragments often show a knife-edged contact between inclusions and matrix, with no mingling or transition. On the other hand, we may have fragments angular or otherwise, which show evidences of replacement in various stages, but which nevertheless are true inclusions (xenoliths), whether in ore veindikes, pegmatite veindikes or granites. The fact is, apparently, that in a veindike or dike, included fragments which have reposed long in the fluid magma are corroded and replaced, and it may be rounded; those which were picked up directly before the freezing stage may be angular, with sharp contacts, and uncorroded. Similarly, in replacement veins where the replacement starts along a network of fractures, angular residua are apt to mark the earlier stages of replacement; later the tendency is more and more to irregular outlines.

The example exhibited by Professor Bateman, showing angular residua of replacement, involves a preliminary fragmentation, for the veinlets which separate the rock pieces must have started along pre-existing fissures in order to have this rectilinear form.

Mr. Graton: We are indebted to Professor Bateman for setting forth so clearly the necessity for a distinction which without doubt many of us have been making somewhat loosely. In this connection, attention may be called to the last paper printed on the program, by Dr. Alfred Wandke, entitled "Shattering by Replacement," in which something of this same conclusion is suggested among other ideas with respect to replacement.

So long as each of the replacing veinlets remains narrow it is likely to be strongly governed as to precise width and parallelism of opposite walls by the position of the central fracture from which it started to form, and the intersection of such parallel-walled veinlets will produce the angular inter-vein shapes which Professor Bateman emphasizes. With continuation of the replacing process, however, by progressive widening of each individual replacement veinlet, the exact control by the central fracture diminishes, the veinlet becomes less regular in width, its opposite walls depart more and more from parallelism, sharp angles or cusps of the inter-vein material begin to yield at a faster rate than elsewhere, and finally the angular shape of these inter-vein areas may be obliterated and changed to the more rounded outline that has so commonly been associated with replacement residues. In short, angular shapes are

likely to be produced in early stages of replacement but considerably less likely to retain marked angularity in the more advanced stages.

Yet ordinarily only in the advanced stages when the residual material constitutes but a small fraction of the total volume, are the residual masses likely to be mistakable at all for foreign or transported inclusions. That is to say, "inclusions" in a *predominant* matrix are likely to be more or less rounded if residues of replacement; and strictly angular inclusions in a *predominant* matrix are perhaps more likely to be imported than to be replacement residues. I fully agree, however, with Professor Bateman that angular replacement residues can and do persist, in some instances, until replacement is complete.

As for the transitional boundary as a criterion of replacement, I think Mr. Spurr will agree that very frequently replacement is complete so far as it goes and will yield as sharp, abrupt contacts as can be produced by simple filling of open spaces.

ALASKAN NICKEL MINERALS.[1]

A. F. BUDDINGTON.

INTRODUCTION.

A SUITE of specimens collected from outcrops of several recently discovered nickeliferous pyrrhotite deposits in southeastern Alaska was studied by the writer with the aid of the metallographic microscope. Great difficulty was found in reaching a suitable interpretation of the nature and relations of the minerals present. For comparison, suites of specimens showing similar minerals from the Gap Mine in Lancaster County, Pa., the Friday Mine, near Julian, California, and the Sudbury district were studied. Certain conclusions were reached and were submitted for publication when, through the courtesy of the editor, Dr. A. M. Bateman, the writer was permitted to see the proof of a paper, in press, by Lindgren and Davy on "Nickel Ores from Key West Mine, Nevada." At the same time a paper by Wandke and Hoffman[2] on "A Study of the Sudbury Ore Deposits" appeared. Adequate evidence was here presented, for the first time to the writer's knowledge, of a certain type of extensive "supergene alteration" of the primary nickel mineral, pentlandite. The present article embodies the data contained in the original paper prepared by the writer, and a revision of certain interpretations, made in the light of the new evidence brought forward in the papers cited.

In part only a statement of problems encountered by the writer in his study of the nickel minerals is made, since no solution was obtained.

The writer is indebted to Edward Sampson of the U. S. Geological Survey for the personal interest which prompted him to

[1] Published by the permission of the director of the U. S. Geological Survey.

[2] Wandke, Alfred, and Hoffman, Robert, "A Study of the Sudbury Ore Deposits," ECON. GEOL., vol. XIX., 1924, pp. 169–204.

spend considerable time and labor in securing and having prepared many specimens of sulphide ore, including R. M. Overbeck's samples from the Alaska Nickel mine and Canyon Creek, Alaska; Sudbury polydymite and Creighton ore from F. L. Hess; bravoite, and Sudbury and Grünau polydymite from the U. S. National Museum; bravoite from D. F. Hewett; and in permitting the use of his own collection from the Gap Mine, Pennsylvania. Professor Lindgren courteously furnished the writer polished specimens from the Key West Mine, Nevada, and from Sudbury. Professor A. H. Phillips of Princeton University very kindly offered to do the analytical work, and the writer is under obligations to him for the four chemical analyses appearing herein. The author is also indebted to E. L. Perry for specimens from Dracut, Massachusetts, to Professor G. M. Schwartz for a specimen from the Pigeon Point region, Minnesota, and to John F. Walker for the photomicrographs.

The writer's conclusions are that a nickel mineral secondary after pentlandite, and commonly called polydymite in the literature, is present in many of the outcrops of nickeliferous pyrrhotite bodies. In one case it will be shown that this mineral is a disulphide of iron and nickel and that it is probably identical with bravoite. The writer believes that the criteria previously used in the identification of this mineral with polydymite are not valid. Lindgren and Davy, and Wandke and Hoffman are followed in ascribing a supergene origin to the mineral.

NICKEL MINERALS AND THEIR PROPERTIES.

The interpretation of the Alaskan nickel minerals involves a consideration of the known nickel minerals; pentlandite (Fe, Ni)S; polydymite Ni_4S_5; and bravoite (Fe, Ni)S_2; and of the possible nickel minerals; violarite NiS_2(?) as recently proposed by Lindgren; and an iron-rich mineral with the polydymite type of formula $(Ni, Fe)_4S_5$.

Pentlandite.—The primary nickel mineral of the Alaskan deposits is probably predominantly, if not entirely, pentlandite. It occurs both in the massive sulphide masses and in disseminated blebs of sulphide in the country rock.

An effort was made to determine the chemical composition of the pentlandite in the disseminated sulphides of the Bohemia prospect on Yakobi Island. Several hand specimens of the "disseminated norite" from the Bohemia tunnel were crushed and the sulphides picked out by hand. The latter were then ground in a mortar and the pyrrhotite separated with an electro-magnet. The pyrrhotite was found to be only weakly magnetic, but the pentlandite was non-magnetic. Only 300 milligrams were thus obtained, and the amount of impurity could not be ascertained. A little pyrrhotite was probably present.

CHEMICAL ANALYSIS OF PENTLANDITE, YAKOBI ISLAND, ALASKA.
Analyst, A. H. Phillips.

	I	Ia	Ib
Insoluble	5.83		
Cu	2.70		
Ni	21.28	24.65	0.420
Fe	35.10	37.88	0.678
S*	35.09	37.47	1.170

* Sulphur by difference.

I. Non-magnetic concentrate from sulphides of disseminated norite, Bohemia Claims, Yakobi Island, Alaska.

Ia. Composition of pentlandite calculated free of chalcopyrite and silicates.

Ib. Atomic ratio.

As shown by the atomic ratios, the mineral conforms within the limits of error to the formula for pentlandite (Ni, Fe)S with a ratio for iron to nickel of about 5 to 3. With the metallographic microscope, the mineral is observed on a polished surface to have a creamy white color, 3 intersecting cleavage traces interpreted as the traces of an octahedral parting, a hardness of 4, and is brittle. Microchemical tests give the following results; with concentrated HNO_3 the mineral turns successively through brown with orange hues, and purple, to a characteristic blue-violet or cadet blue; with KCN, KOH, $FeCl_3$, $HgCl_2$, and HCl, negative. These properties are similar to those of the pentlandite from the Sudbury district.

Polydymite.—The original polydymite is found at the Grünau mine in the Siegen district of Westphalia, Germany. A specimen from this locality was obtained from the U. S. National Museum. The polished surface has a creamy white, near white, color in reflected light; effervesces slowly with HNO_3, develops a marked structure locally, and rubs to a blue gray; with HCl gives a green color to the acid; negative with KOH, KCN, $FeCl_3$, and $HgCl_2$. The hardness of the polydymite is given by Dana as 4.5. It is, however, considerably harder than the so-called Sudbury polydymite; the Alaskan bravoite; or the secondary nickel mineral at the Gap Mine, Pennsylvania; Dracut, Massachusetts; Pigeon Point region, Minnesota; and the Bohemia, Tasmania, and Snipe Bay prospects, Alaska. It has about the same hardness as the nickel mineral in the sulphide ores of the Friday Mine, California. It is non-magnetic with respect to the same electro-magnet which attracted the secondary nickel minerals from several of the localities mentioned.

Its existence was not positively determined in any of the pyrrhotite specimens studied.

Bravoite.—R. M. Overbeck[8] has described a nickeliferous mineral deposit associated with peridotite about 15 miles southeast of Chitina, Alaska, in the vicinity of Spirit Mountain near the head of Canyon Creek, a tributary of the Copper River. Overbeck described the nickel mineral as non-magnetic, occurring in roughly equidimensional grains that show cubic cleavage and in slender stringers cutting through the pyrrhotite. He separated the nickel mineral by picking out the grains as seen on a polished surface, and separating the attached pyrrhotite with a hand magnet from the ground concentrate. This concentrate was analyzed by W. T. Schaller and found to be only slightly soluble in HCl. Overbeck concluded that the sample analyzed was impure, that apparently two nickel minerals were present, and that their formulas and names cannot even be surmised.

It seemed advisable to make another effort to determine the nature of this mineral. A sample of one of Overbeck's speci-

[8] Overbeck, R. M., "Nickel Deposits in the Lower Copper River Valley, Alaska," U. S. Geol. Survey, Bull. 712–*c*, 1919.

mens was ground, and the material between 40 and 100 mesh subjected to an electromagnet. A sample of the relatively weak magnetic concentrate was then mounted in wax, polished and examined with the reflecting microscope. The concentrate was estimated to consist of 2½ per cent. limonite, 6½ per cent. chalcopyrite, 8 per cent. pyrrhotite, some silicate, and about 80 per cent. of the unknown nickel mineral. Doubtless a little of the secondary alteration product of the nickel mineral was also present, but this could not be computed and is ignored in the recalculations.

CHEMICAL ANALYSIS OF BRAVOITE.

Analysis I by A. H. Phillips.

	I	I*a*	I*b*	II	III
Insoluble.....	2.78			1.2	
Cu.....	2.38			.7	
Ni.....	19.84	24.81	0.422	19.6	18.23
Fe.....	25.08	20.68	0.370	28.4	29.46
S*.....	49.92	54.51	1.700	50.1	52.31
	100.00	100.00		100.00	100.00

* Sulphur by difference.

I. Weakly magnetic concentrate (80 per cent. bravoite) from nickeliferous mineral deposit at Canyon Creek, Copper River, Alaska.

I*a*. Composition of Bravoite calculated with elimination of impurities.

I*b*. Atomic Ratio.

II. Composition of relatively non-magnetic concentrate obtained by Overbeck. Analyst, W. T. Schaller.

III. Composition of Bravoite from Minasragra, Peru, calculated with elimination of impurities. Analyst, W. F. Hillebrand.

The concentrate obtained by Overbeck apparently contained somewhat more pyrrhotite than that of the writer, but is otherwise similar. The writer, from a metallographic study of the concentrate, does not believe that the slight solubility of the nickel in HCl found by Schaller necessarily means that a second nickel mineral is present in such quantity as to render unwarrantable an attempt to derive a formula. The nickel mineral conforms, within the limits of error involved, to the formula $(Ni, Fe)S_2$. The only mineral approximating this composition is one described by

Hillebrand[4] from specimens furnished by D. F. Hewett from the vanadium deposits at Minasragra, Peru. The analysis, calculated with elimination of impurities, is given in (III). The general formula $(Ni, Fe)S_2$ is the same for both the Alaskan and Peruvian minerals, but the ratio of iron to nickel is about 3 to 5 in the latter and a little more than 1 to 1 in the former.

The Peruvian "bravoite" is described by Hillebrand as very insoluble in HCl but readily soluble in HNO_3; whiter in color than pyrite, tarnishing with a reddish cast; crystals in a few instances with an octahedral habit; not attracted by a hand magnet, but attaches itself readily to an electro-magnet. The density of the material analyzed is 4.33, but this is not considered accurate because of impurities. Hot water extracts from the powder ferrous and nickelous sulphates. Hillebrand writes that the mineral is to be regarded as a nickeliferous pyrite and that "should it seem proper to give it a specific name later, 'bravoite' is suggested, after Senor Jose J. Bravo, the Peruvian writer on the Vanadium occurrence at Minasragra."

The writer obtained a small sample of this mineral from the U. S. National Museum, and examined it on a polished surface with the reflecting microscope. The mineral occurs as grains in "quisqueite." With reflected light it has a pallid gray color with a violet hue, and shows three well defined intersecting cleavages. Its hardness is a little less than 5. Microchemical tests gave the following results; concentrated HNO_3—effervesces and turns blue gray; HCl, $HgCl_2$, KCN, KOH, and $FeCl_3$—negative. One grain reacted slightly with KOH and rubbed faint brown.

Overbeck described the Canyon Creek, Alaska, mineral as nonmagnetic. The writer prepared the concentrate for analysis by separating the pyrrhotite from the unknown nickel mineral with an electromagnet, and only subsequently found that the nickel mineral itself was weakly magnetic, and that a clean separation from chalcopyrite could be made because of the difference in their magnetic properties. The density of the Alaskan mineral, as determined for the writer by A. H. Phillips is 4.31. Water leaches out ferrous and nickelous sulphates.

[4] Hillebrand, W. F., *Am. Jour. Sci.*, ser. 4, vol. XXIV., p. 151, 1907.

Examined with the reflecting microscope on a polished surface, the fresh mineral has: a pale dull gray or grayish white color similar to that of the Grünau polydymite; three cleavage traces; * a hardness of about 4 ½; and reacts as follows with microchemical tests; conc. HNO_3—effervesces and rubs blue gray; KOH, $FeCl_3$, $HgCl_2$, and KCN—negative; HCl—acid turns yellow slowly but rubs clean. The freshest mineral is associated with that portion of the ore in which marcasite is partially replacing the pyrrhotite. The mineral where marcasite is absent may have a violet hue and rubs brown after tests with KCN. This difference is probably the result of weathering.

The Alaskan mineral thus has similar properties and chemical formula to the "Bravoite" of Peru and it is considered a variety of that mineral with a somewhat higher percentage of the nickel component in solid solution.

Sudbury Polydymite (*Violarite*).—Clark and Catlett[5] described and analyzed an iron gray nickel mineral found at the Vermillion mine in the Sudbury district. Their analysis worked out to the formula Ni_3FeS_5 or $(Ni, Fe)_4S_5$, which corresponds to the polydymite type. For this reason the mineral was called polydymite.

Lindgren and Davy re-studied specimens of similar character, and found the material to be a mixture of pentlandite and a gray mineral in about equal proportions. Lindgren suggests that the gray mineral is not polydymite, but a new mineral with a possible formula of NiS_2(?), though not much weight is attributed to the probable correctness of the formula. He proposed the name violarite to designate this mineral.

Several specimens of so-called polydymite from the Sudbury district were obtained by the writer from Ward's Natural Science Establishment. These showed the minerals pentlandite, a gray nickel mineral, chalcopyrite, galena, and pyrite.

* Dr. Edward Sampson examined a specimen for the writer with polarized reflected light and could detect no anisotropism.

[5] Clark, F. W., and Catlett, C., *Am. Jour. Sci.*, vol. XXXVII., 1889, pp. 372–374.

The freshest portion of the predominant nickel mineral is grayish white in color with reflected light from the polished surface. That portion intimately involved with the pentlandite is a pale bluish-gray color with a violet hue. The supposed violarite or polydymite has three intersecting cleavage traces, a hardness of 4 to 4 ½; is non-magnetic with a small electro-magnet; effervesces with HNO_3, and rubs to a blue gray with locally a violet hue.

In order to find out positively whether this mixture of minerals was similar to that analyzed by Clark and Catlett, a specimen was crushed and the gray mineral fragments picked out by hand. Unfortunately, the presence of galena in grains of some size was not suspected, and they were concentrated along with the gray mineral, thus accounting for the high lead content shown in the analysis. In a similar effort to get at the composition of the gray mineral, an analysis of a mixture of pyrite and the gray mineral was made.

ANALYSES OF NICKEL MINERALS WITH ADMIXTURES.
Analyst, A. H. Phillips.

	I	Ia	Ib	II	IIa	IIb	III
Insoluble....	Trace			.90			
Cu.....	.44			Trace			
Ni.....	21.94	22.47	.382	41.48	48.68	.828	43.09
Pb.....	.50			12.03			
Fe.....	27.00	27.24	.491	14.57	17.00	.307	17.26
S.....	50.12*	50.29	1.571	31.02*	34.32	1.076	39.76

* Sulphur by difference.

I. Mixture of pyrite and unknown nickel mineral, Sudbury district.

Ia. Recalculated with elimination of galena and chalcopyrite.

Ib. Atomic ratios.

II. Mixture of gray nickel mineral, pentlandite, and galena.

IIa. Recalculated with elimination of galena and insoluble.

IIb. Atomic ratios.

III. Analysis of Sudbury polydymite by Browne, corrected for admixed chalcopyrite.

The analyses confirm the probability of Lindgren's suggestion that the supposed mineral analyzed as polydymite by Clark and Catlett and by Browne was actually a mixture of two or more

minerals. The mixtures are so intimately intergrown that no accurate quantitative estimate could be made of their composition, and the analyses are confusing.

One interpretation, considering probable mixtures, would be that both a disulphide compound (bravoite ?) and polydymite existed in the ore, and that the material previously analyzed by Clark and Catlett and by Browne contained some pyrite and perhaps some disulphide nickel compound in addition to pentlandite. But the data are inadequate to arrive at a probable formula for the unknown nickel mineral or minerals, and the problem is unsolved.

Nickel Mineral X.—Wandke and Hoffman [6] have described the replacement of pentlandite by a mineral which they call polydymite in the upper workings of the Levack Mine in the Sudbury district. Lindgren and Davy [7] have described a secondary nickel mineral, at first called polydymite and later "violarite" by Lindgren, from the Key West Mine, Nevada. Professor G. M. Schwartz [8] states that a mineral with similar properties to the so-called polydymite of Sudbury partially replaces pentlandite in a sulphide mass in Cook county, Pigeon Point region, Minnesota.

The writer, similarly, has found a nickel mineral which is secondary after pentlandite in the surface outcrops of sulphide masses at the Gap Mine, Pennsylvania, and the Tasmania, Bohemia, and Snipe Bay prospects in Southeastern Alaska, and has studied a similar mineral in specimens of sulphide ore from Dracut, Massachusetts. Though the courtesy of Professor Schwartz and Professor Lindgren, he has also been permitted to study specimens from the Pigeon Point region, Minnesota, and from the Key West Mine, Nevada.

The secondary nickel mineral from all the localities cited has similar characters and microchemical reactions when studied under the metallographic microscope, and as shown in the table of properties these are similar to those of bravoite. There is, however, a peculiar feature connected with the results of testing

[6] *Loc. cit.*, p. 191.

[7] *Loc. cit.*

[8] Personal communication. See also *Am. Mineralogist*, vol. 9, 1924, p. 32–33.

TABLE SHOWING PROPERTIES OF SOME NICKEL MINERALS.

	POLYDYMITE (Grünau, Westphalia).	POLYDYMITE? (VIOLARITE?) (Sudbury, Ont.).	POLYDYMITE? (Friday Mine, Cal.).	BRAVOITE (Minasragra, Peru).	BRAVOITE (Canyon Creek, Alaska).	NICKEL MIN. X (Snipe Bay, and Bohemia Basin, Alaska; Gap Mine, Pa.; etc.).
Cleavage Traces	3	3	3	3	3	3
Hardness	5–	4½	5	5–	4½	4½
Magnetic	–	–	+	+	+	+
HNO_3 (Effervesces, and rubs blue gray)	+	+	+	+	+	+
HCl (Acid turns yellow or green, rubs clean.)	+	+	+	–	+	+ª
KCN (Rubs brown)	–	–	–	–	∓ª	–
KOH	–	–	–	–	–	–
$FeCl_3$	–	–	–	–	–	–
$HgCl_2$	–	–	–	–	–	–

+ Positive. ª — Fresh mineral, negative; weathered mineral, positive.
– Negative.

this mineral with KCN. At the Snipe Bay and Tasmania prospects in Alaska, where the mineral is in part associated with marcasite replacing pyrrhotite, it rubs brown after testing with KCN, whereas what is apparently the same mineral rubs clean after testing with the same solution where it occurs in the pyrrhotite not replaced by marcasite. This difference, as in the case of the bravoite at Canyon Creek, is attributed to weathering.

Several serious but unsuccessful attempts were made to isolate some of the secondary nickel mineral X for analysis. In the case of the Snipe Bay, Alaska, and the Gap Mine sulphides, the nickel mineral was too strongly magnetic to separate from the pyrrhotite. The pyrrhotite of the Friday mine was in part less magnetic than the nickel mineral and in part more magnetic, but is itself only weakly magnetic.

On the basis of its similarity in characters when studied with the reflecting microscope, Lindgren has identified the secondary nickel mineral at the Key West Mine, Nevada, with the Sudbury polydymite or violarite.

The secondary nickel mineral at the Gap Mine, Pennsylvania, and the Snipe Bay and Bohemia prospects in Alaska, is weakly magnetic, and to this extent differs from the Sudbury mineral, though in its microchemical reactions and hardness it is similar. It may be noted furthermore that in its microchemical reactions it is equally similar to "bravoite," though it is a trifle softer. Also, as in the case of "bravoite," the nickel mineral X often tarnishes to a copper red resembling niccolite. The similarity of polydymite to nickel mineral X adds a further possible source of confusion.

To emphasize the present uncertain identity of this mineral, the writer prefers to use in this paper the term "nickel mineral X," instead of possibly wrongly identifying it with either "bravoite," polydymite, or violarite. It may be that more than one mineral is thus included under the term "nickel mineral X."

INTERRELATIONS OF MINERALS.

Bohemia Prospect, Yakobi Island, Alaska.—At the Bohemia claims the sulphides occur in part disseminated as blebs in norite

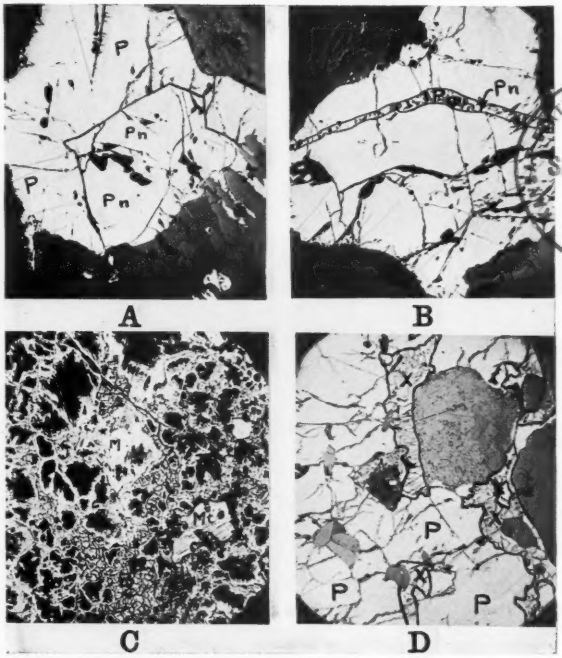
EXPLANATION FOR PLATE IX.

A. Bleb of sulphides in hypersthenite, Yakobi Island, Alaska. Fibers oriented along cracks are secondary pentlandite. Pentlandite (Pn) with crystal faces against pyrrhotite (P). × 23.

B. Bleb of sulphides in hypersthenite, Yakobi Island, Alaska. Veinlet of pentlandite (Pn) crossing pyrrhotite. Veinlet outlined in black. × 23.

C. Nickel mineral X (B, granular) in pyrrhotite (black) partially replaced by marcasite (M, white). Magnetite (Mt) with ilmenite intergrowths corroded by sulphides. Snipe Bay, Baranoff Island, Alaska. × 23.

D. Nickel mineral X (X, outlined in black). secondary replacement after pentlandite in pyrrhotite (P). Gap Mine, Pennsylvania. × 23.



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very rich in hypersthene and in olivine hypersthenite, and in part within lenses within the norite in which the sulphides predominate.

Samples of fresh "disseminated rock" from a tunnel which cuts it 200 feet below the outcrop were studied. This consists of about 12 per cent. labradorite ($Ab_{35}An_{65}$), 4 per cent. sulphides, and bronzite (86 per cent. $MgSiO_3$), monoclinic pyroxene, hornblende, olivine, and a little biotite and interstitial quartz. The bronzite is the predominant mineral. Another type consists of about 80 per cent. bronzite, 10 per cent. olivine, 1 ½ per cent. sulphides, and monoclinic pyroxene. The disseminated sulphides form irregular blebs interstitial to, but replacing, the silicates, and locally sending off threads between and across them. The sulphides actually appear to belong to the last stage of magmatic crystallization associated with the interstitial plagioclase, despite the fact that they show replacement relations against the silicates.

Specimens from three different localities on the Bohemia claims, consisting of norite or hypersthenite with "disseminated" sulphides, were studied. Two of these were from the actual surface outcrop. The sulphides comprise pyrrhotite, pentlandite, and chalcopyrite. The pyrrhotite predominates, but pentlandite forms a considerable proportion of the blebs. In no case did the pentlandite show any trace of alteration, even on surfaces only a half inch below the weathered surface. The pentlandite and chalcopyrite tend to occur predominantly along the borders of the sulphide blebs. The pentlandite occurs as grains which usually show straight line borders against the pyrrhotite, suggesting the traces of crystal faces (Plate IX, A). The pentlandite and chalcopyrite show mutual relations to each other. The chalcopyrite, in part, shows mutual relations to the pyrrhotite, and in part straight line borders, suggesting crystal faces. In one sulphide bleb a veinlet of pentlandite crosses its full length and cuts the pyrrhotite (Plate IX, B). All three minerals appear to belong to the same period of mineralization; the pentlandite and chalcopyrite perhaps beginning early and finishing late. A second

generation of pentlandite is present in small amounts. It replaces the pyrrhotite locally along the borders of the chalcopyrite and first generation pentlandite, and occurs in needle-like shapes along cracks or in patches with deeply serrate borders. An alternative explanation for the mineral relations shown is that the pentlandite and chalcopyrite are both later than the pyrrhotite, and that the crystal faces of the pentlandite against the pyrrhotite are the result of replacement. This is a complex interpretation for which there does not seem to be any supporting evidence.

Specimens from the surface outcrop of the sulphide ore naturally show considerable alteration. The metallic minerals comprise pyrrhotite, pentlandite, nickel mineral X, chalcopyrite, marcasite, niccolite, and limonite. The niccolite occurs as occasional minute copper red specks along fracture surfaces in the ore, and was not noticed on polished surfaces. The pyrrhotite, nickel mineral X, and chalcopyrite "appear" to have been essentially contemporaneous in crystallization. The nickel mineral X, however, is actually secondary after primary pentlandite. The nickel mineral X occurs in granules of equidimensional to stringer-like form. The equidimensional grains show definite straight line borders against the pyrrhotite and appear to be the traces of crystal faces. Only a trace of pentlandite was found in the specimens examined, but the form of the nickel mineral X resembles the mode of occurrence of the pentlandite grains in the sulphide blebs of the "disseminated" rock.

The marcasite, where present, replaces the pyrrhotite and works into it from the grain boundaries. Where the marcasite borders the nickel mineral there is practically no evidence of replacement. The latter retains its straightness and definiteness.

Tasmania Claims.—At the Tasmania claims located in the Bohemia Basin on Yakobi Island, masses of solid sulphides are associated with norite. One specimen examined of the country rock consists of about 75 per cent. pyroxene in a much altered condition and 25 per cent. labradorite. The pyroxene (probably originally bronzite) is almost wholly altered to a microcrystalline aggregate of talc and fibrous uralite.

Several specimens were examined from a three foot mass of solid sulphide. An analysis made for the writer by E. T. Erickson, of the chemical laboratory of the U. S. Geological Survey, gave 4 per cent. nickel and 0.8 per cent copper. The minerals comprise pyrrhotite, nickel mineral X, pentlandite, chalcopyrite, and marcasite. The marcasite is secondary and replaces the pyrrhotite, forming an intricate network of veinlets. The nickel mineral X shows only a trace of replacement by the marcasite. In part, the replacement of the pyrrhotite starts from the borders of the nickel mineral and works inward. The nickel mineral X for the most part forms a much interrupted skeletal network to the pyrrhotite grains. In part it occurs as grains about the same size as those of the pyrrhotite. Some of these are clot-shaped, with apophyses running out as tentacles between the adjoining pyrrhotite grains. Almost all of the nickel mineral X contains residual remnants of partially replaced pentlandite. It is no doubt secondary after pentlandite, and the alteration has taken place without migration or replacement of the pyrrhotite. The chalcopyrite is, in part, in grains contemporaneous with the pyrrhotite and pentlandite. Nickel mineral X and chalcopyrite form veinlets crossing the silicates. The nickel mineral associated with the marcasite rubs brown with KCN, whereas the nickel mineral X in the sulphides, without marcasite, gives a negative reaction.

Alaska Nickel Mines.—The nickel deposits of the Alaska Nickel Mines on Fleming Island off the coast of Chicagoff Island in Southeastern Alaska have been described by R. M. Overbeck.[10] The ore deposits are associated with diorite and norite. The interrelations of the sulphides are described by R. M. Overbeck as follows: "A polished surface of the ore shows pyrrhotite, pentlandite, and chalcopyrite. . . . At no place in a dozen specimens examined could any decisive evidence as to the relative time of formation of the sulphides with reference to one another be obtained. . . . They are, however, definitely later than the original

[10] Overbeck, R. M., "Geology and Mineral Resources of the West Coast of Chichagoff Island," U. S. Geol. Survey Bull. 692, pp. 125–133, 1919.

silicates." The writer found that the pentlandite occurs as grains, as blebs with offshooting fingers, and as vein-like stringers interstitial to the pyrrhotite grains. Locally blebs of pyrrhotite are enclosed by the pentlandite veinlets. The pentlandite appears in part to be contemporaneous and in part, together with the chalcopyrite, to have finished crystallization last.

Snipe Bay.—At the Snipe Bay locality on Baranoff Island, the nickeliferous mineral deposits are associated with a small mass of amphibolite or highly hornblendic gabbro, intrusive into schists. The rock adjacent to the massive sulphide ore consists of about one-third ilmenitiferous magnetite. The sulphide ore is in part so coarse-grained and weathered, and in part so altered to marcasite, that good polished surfaces to show the texture were not obtained. Pyrrhotite, nickel mineral X, and chalcopyrite were identified. The pyrrhotite is locally completely replaced by marcasite, and the nickel mineral X is left as interrupted skeletal network and as clot-shaped grains in the marcasite (Plate IX, C). The magnetite in part shows parallel rod-shaped intergrowths of ilmenite of microscopic size on a polished surface. It is earlier than the sulphides and is partially replaced by them. Locally, it appears as though the silicates originally associated with the magnetite had been almost entirely replaced and that resistant remnants of the relatively more insoluble magnetite alone had remained. Chalcopyrite occurs as veinlets in the rock adjoining the sulphide masses, and is therefore probably in part of later crystallization than the other sulphides, marcasite excepted.

Canyon Creek, Alaska.—New polished sections were made for the writer from Overbeck's specimens. The chief minerals are pyrrhotite, chalcopyrite, and bravoite, the pyrrhotite predominating. The bravoite is altered on the borders to a mineral with a violet gray color. The bravoite occurs, as essentially described by Overbeck, in roughly equidimensional grains, as slender stringers interstitial to the pyrrhotite grains, locally as a rim to the pyrrhotite grains, and as clot-shaped blebs fingering in between them. Bravoite grains occur in sizes up to one-half inch in diameter. Locally distinct veinlets of bravoite, with local en-

largements, traverse the pyrrhotite. Chalcopyrite occurs as blebs in the larger grains of bravoite, and is disseminated through the pyrrhotite. In part, the chalcopyrite and bravoite appear to definitely replace the pyrrhotite. Marcasite locally veins and partially replaces the pyrrhotite.

Friday Mine.—The nickel ores of the Friday Mine near Julian in San Diego County, California, have been studied by F. C. Calkins[11] Tolman and Rogers,[12] and Hudson.[13]

The following quotation is from Tolman and Rogers.[14]

> The polished sections of the massive ores consist largely of pyrrhotite with residual spots of silicates. Associated with the pyrrhotite is a considerable amount of pentlandite. Calkins reported this as polydymite, but it has the characteristic cleavage, relief, and color of pentlandite. A second generation of pentlandite is developed along cracks in the pyrrhotite. A brass yellow mineral occurs in veinlets and reticulate masses as a replacement of pyrrhotite. This was called pyrite by Calkins, but more probably is marcasite. The marcasite gives the impression of being a very late mineral.

Hudson states (p. 177) that "secondary sulphides are present in small amount, but their development has probably added little or nothing to the valuable metal content of the ore." He describes the disseminated sulphides in the country rock as consisting of pyrrhotite, chalcopyrite, and pentlandite, and the sulphides of the massive ore as consisting of pyrrhotite, polydymite (?), and chalcopyrite. Another of his conclusions is that though the polydymite and chalcopyrite show some tendency to occur in veinlike forms, there is no evidence that they were introduced from without after the solidification of the pyrrhotite.

The writer examined Calkin's specimens of massive sulphide, and verified Calkin's and Hudson's determination of the nickel mineral as some mineral other than pentlandite and with proper-

[11] Calkins, F. C., "An Occurrence of Nickel Ore in San Diego County, California," Bull. 640, U. S. Geol. Survey, pp. 77–82 (1916).

[12] Tolman and Rogers, "A Study of the Magmatic Sulfid Ores," Leland Stanford University Pub. 1916, pp. 40–41.

[13] Hudson, F. S., "Geology of the Cuyamaca Region of California," Pub. Univ. of Calif., vol. 13, 1922.

[14] *Loc. cit.*, pp. 40–41.

ties similar to polydymite. Its properties are also very similar to those of bravoite. A serious but unsuccessful effort was made to separate the nickel mineral from the pyrrhotite with an electro-magnet. But it was found that both the nickel mineral and the pyrrhotite were weakly magnetic; and that although both could be separated from chalcopyrite, they could not be separated from each other. With the same electro-magnet, the Grünau polydymite showed no attraction. The identity of the mineral is an unsolved problem.

One specimen two inches long shows a veinlet of chalcopyrite running the full length, with several ramifying branches. To a considerable extent the chalcopyrite appears to have come in along fractures determined by the location of pre-existing veinlets of nickel mineral, for the nickel mineral occurs here and there along one or both sides of the chalcopyrite and parallel to it. The chalcopyrite shows locally evidences of replacement of the nickel mineral. The latter occurs in part along the boundary of the pyrrhotite grains, but in part sends off fingers parallel to the parting of the pyrrhotite. Marcasite occurs as veinlets replacing the pyrrhotite. At Gap Mine and at the Bohemia prospect the primary nickel mineral, pentlandite, is found in the "disseminated rock," and a secondary nickel mineral in the massive sulphide ore. The occurrence at the Friday Mine of pentlandite in the disseminated sulphide rock, and of a different nickel mineral in the massive sulphide ore, is an analogous relation. In the light of the new evidence now at hand in regard to the origin of secondary nickel minerals at other localities, a review of the evidence at the Friday Mine would be valuable.

Gap Mine.—In specimens from the surface outcrops, the pentlandite is predominantly, in part or in whole, altered to nickel mineral X (Plate IX, D). The alteration has proceeded along, and has worked in from, the parting planes of the pentlandite. In this process there has been no blurring or production of irregularities in the borders of the grain. A trifle of secondary pentlandite (?) is present as fibers along the borders of the secondary nickel mineral and crystallographic directions of the pyrrhotite,

and oriented at right angles to them. The pyrrhotite is also replaced, to a trifling extent, by marcasite. In a specimen of sulphide ore, with many rounded nodules of rocks, grains of unaltered pentlandite still remain within the nodules. In this specimen carbonate aggregates are found partially replacing the pyrrhotite. It is significant that the first generation pentlandite is restricted to interstitial relations to the pyrrhotite, whereas the secondary pentlandite works into the pyrrhotite along its crystallographic directions.

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Sudbury.—The writer studied specimens of supposed polydymite from the Sudbury district, obtained from Ward's Natural Science Establishment, the U. S. National Museum, F. L. Hess, and Waldemar Lindgren.

The U. S. National Museum specimen is seen with the eye alone to consist of a gray mass with a few well-marked, reticulating veinlets consisting of pentlandite and chalcopyrite. With the microscope the gray areas are found to consist predominantly of a mineral with a pale grayish white color, with a faint brownish or violet hue, a hardness of about 4½, and three conspicuous cleavage traces. This mineral corresponds to the polydymite of former writers and the violarite of Lindgren. To the writer it appears as though the pentlandite had attacked and partially replaced the violet-gray mineral and that in the process the latter tends to lose the distinctness of its conspicuous cleavage, takes on a bluish gray color and becomes merged with the pentlandite. The chalcopyrite tends to occur in the center of the pentlandite veinlets, and is believed to be later.

Several specimens obtained from Ward's were examined and interpreted as follows. Without the microscope the polished surface shows granules of gray mineral in a reticulating meshwork of pentlandite veinlets. Occasional pyrite veinlets cut across both the gray mineral and the pentlandite. With the microscope the gray mineral is seen to have its cleavages faced with a gangue mineral or minerals. The pentlandite works in along and parallel to this gangue matter and replaces the gray mineral. Often, rods of the gangue are left projecting into the

pentlandite or a lattice work of gangue is left residual in the pentlandite. The cleanest and largest areas of the pentlandite contain no gangue arranged along cleavages. Blebs of galena occur in the pentlandite and the gray mineral. The pyrite is the youngest mineral and veins and shows replacement relations against all the other minerals.

A specimen obtained from F. L. Hess "appears" to show the reverse relation of the pentlandite to the violet-gray mineral. That is, the gray mineral, when examined under the microscope "appears" to be replacing the pentlandite. Without the microscope, however, the specimen shows the usual appearance of granules of gray mineral in a reticulating network of pentlandite veinlets.

Tolman and Rogers[15] describe polydymite and an unknown violet-gray mineral as resulting from the breakdown of pentlandite. Lindgren,[16] similarly, states that he believes the violet-gray mineral to be secondary after pentlandite.

The writer has neither the material nor the field data to warrant a further discussion of this most interesting problem.

GENESIS.

Coleman[17] includes the mineral called polydymite in the Sudbury region, together with the pyrrhotite, chalcopyrite, and pentlandite, as primary minerals. Hudson[18] similarly argues that the polydymite (?) of the Friday Mine, California, is a primary mineral. Lindgren and Davy, on the other hand, came to the conclusion that the so-called polydymite of the Sudbury district and of the Key West Mine, Nevada, was the result of secondary alteration of pentlandite by supergene waters.

Wandke and Hoffman,[19] also in speaking of the Levack mine, write, "In the upper workings of the mine the pentlandite altered to a mineral determined as polydymite. The polydymite is evi-

[15] *Loc. cit.*, p. 33–34.
[16] Personal communication.
[17] *Loc. cit.*, p. 26.
[18] *Loc. cit.*, pp. 224, 228.
[19] *Loc. cit.*, p. 191.

dently due to supergene solutions. Even though the pentlandite may be almost completely altered, the pyrrhotite, chalcopyrite and sphalerite adjoining fail to show any effects of oxidizing solutions. It is entirely probable that the excellent cleavage of the pentlandite made this mineral particularly susceptible to the action of secondary solutions."

The writer was at first of the opinion that the nickel mineral X was a primary mineral resulting from hypogene alteration of pentlandite. The evidence of the secondary origin of this mineral, however, presented by the authors cited, together with further study, has convinced the writer that alteration of pentlandite by supergene waters is probably the proper one. The alteration of the pentlandite to nickel mineral X has, however, taken place in such a fashion that the original form and mode of occurrence of the pentlandite is in many cases almost, if not quite, perfectly preserved. The secondary nickel mineral X has thus come to bear the same relation to the other minerals as the original pentlandite, and has more the appearance of an alteration accompanying the primary formation of the sulphide mass.

The bravoite and nickel mineral X[20] in the pyrrhotite masses appear to have been formed independent of marcasite, but at the same time to have been relatively stable in contact with solutions which produced a partial replacement of adjacent pyrrhotite by marcasite.

It seems to the writer that the polydymite or violarite of the Sudbury region, in its relations to the associated minerals, presents a different set of phenomena from those discussed for the nickel mineral X and bravoite, and that it may possibly have had a different origin.

[20] It is the writer's opinion that in most cases the secondary nickel mineral X is bravoite.

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PRIMARY AND SECONDARY ORES OF THE BOTTINO MINES, ITALY.

CORNELIO L. SAGUI.

History and Location.—The Bottino lead mines are within a short distance of the sea, about thirty miles west of Pisa in the Apuanes Alps. The mines have had a long and varied history, going back to the time of the Etrurians.[1] Under the Roman Empire mining was probably still carried on by the Etrurians, as Rome was more military than industrial.[2] Work in the mines was stopped in the Middle Ages, and little was done until 1829, when there was considerable industrial activity up to the year 1883. Then work was again stopped until in 1918 a new era began.

Geology.—Crystalline schists of Triassic age characterize this region. Their color is gray or partly reddish from the iron oxide contained in them. Quartz and garnet may be readily detected, and tourmaline and mica are of frequent occurrence. The stresses to which the rocks have been subjected may be inferred by the foliation planes, which trend NW.–SE., with a dip to the SW. of 50° to 70°.

The main vein follows the foliation planes and no intrusive rocks are found within a considerable distance. Probably the igneous intrusion that is assumed to have yielded the metallizing solutions never reached the surface.

MINERALOGY OF THE VEIN.

The ore consists of a number of iron, silver, and lead sulphides or sulph-antimonides, and quartz, calcite, and chlorite. Tourmaline in microscopic particles is an abundant constituent of the enclosing rock.

[1] M. L. Simon, *Annales des mines*, 5e Serie, tom, XIV., p. 557, 1858.
[2] C. L. Sagui, *Mem. Soc. Lunigianese G. Capellini*, vol. II., no. IV., 1921.

Gangue Minerals.—The white quartz of the gangue has a rough reniform structure, which points to an intergrowth of idiomorphic crystals with independent centers of formation. The quartz has abundant fluid inclusions and many of them fill the openings completely, which may indicate that the vein was formed under a moderate temperature.

Calcite is not important and is generally mingled with dolomite and quartz. It is interesting, however, that thin threads of jamesonite are frequently enclosed in calcite crystals, suggesting a secondary origin for the calcite.

Chalcopyrite.—This mineral is found occasionally in large crystals and is also seen intermingled with pyrrhotite, galena, blende, and chalcocite.

Pyrrhotite.—This mineral is rather abundant throughout the entire vein. It is of primary origin, as is also the unworkable part of the lode.

Pyrite.—Pyrite is somewhat scanty and as a rule is disseminated throughout the lode in veinlets composed of small grains. Fine crystals are sometimes found, and silver was noted intergrown with pyrite (0.50 per cent. of silver).[3]

Galena.—This is the most important ore-mineral of the mine. It is found throughout the lode, sometimes in compact nests of pure galena, but frequently mingled with specular blende. A noteworthy characteristic is the variety of the grains composing it. In places these grains are almost microscopic in size and the ore appears as a gray and compact mass; frequently the grains are large. Analyses of picked galena specimens are given below:

	Fine Grained	Coarse, I	Coarse, II
Silver	0.325	0.435	0.560
Lead	80.700	78.238	78.284
Iron	1.377	1.828	2.811
Copper	0.440	0.00X	0.00X
Zinc	0.024	—	—
Sulphur	12.840	15.245	15.503
Antimony	3.307	4.431	2.452

[3] E. Bechi, *Acc. Georg.*, N. Serie, vol. III., p. 152, Florence.

Silver is intimately intermingled with galena as silver sulphide,[4] and antimony is always present. Occasionally the large crystals of galena are entirely or partially replaced by an interwoven mass of small needles of meneghenite, which proves the secondary origin of the latter. The following analyses of this material made by the Hollway Laboratory of London[5] may be of interest:

Elements	I	II	III
Lead	39.05	30.90	11.75
Zinc	9.17	9.65	8.51
Copper	2.07	1.80	0.50
Silver	0.093	0.104	—
Cadmium	—	—	—
Cobalt	—	0.43	—
Bismuth	0.20	—	—
Antimony and Arsenic	2.40	2.50	—
Iron oxide (Fe_2O_3)	11.75	16.50	13.95
Cassiterite	0.23	0.20	—

Splendid crystals of galena are occasionally found throughout the entire mass of the ore, which are famous all over the mineralogical world of Europe.

Silver Sulphide.—Some specimens of galena with an unusually high percentage of silver suggested the possibility of finding silver sulphide, and this has been proved true, but very rarely, as far as the personal experience of the writer is concerned. The black sulphide, thinly crystallized, was found in small cavities, vugs and fissures, but in such small quantities that only careful observation in mining may occasionally detect its presence.

Blende.—Zinc blende is also abundant, especially along the foot wall of the vein and within the deeper zones, although it is also found even in the highest levels. Apparently silver diminishes downward as the amount of zinc blende increases.

Jamesonite ($Pb_2Sb_2S_5$)—This is frequently found, especially in crevices, vugs, and fissures. The writer has observed that any large mass of workable ore is preceded by jamesonite, closely

[4] A. Pelloux, *Mem. Soc. Lunigianese G. Capellini*, vol. III., Spezia.
[5] F. Blanchard, *Acc. Lincey*, Rome, 1876.

packed as a felt of long, hair-like crystals where the vein begins to open.

Analyses[6] prove the intergrowth of stibnite needles with jamesonite. This intergrowth is so intimate that it has been found within individual crystals, pointing to the simultaneous deposition of the two minerals.

Meneghenite ($Pb_4Sb_2S_7$).—This ore is rather frequently found, but few crystallized specimens are met with. When found in hair-like crystals, meneghenite is hardly distinguishable from jamesonite. In the writer's opinion there must be other intermediate minerals between jamesonite and meneghenite; possibly boulangerite[7] would come within these limits. The following analysis of a doubtful mineral suggests this conclusion:

Lead	52.012
Antimony	24.630
Sulphur	19.426
Copper	3.450
Iron	0.512

Far-reaching results may be obtained in studying hypogene minerals and their alteration products by observing the crystals of a series such as lead and antimony. Microscopical observations on the crystallographic forms may be sufficient to determine the chemical composition of a certain elementary particle taken within a zone between primary and secondary ores, where transformation is still taking place. The sulphantimonides, sulpharsenides, sulphobismuthites, and probably minerals of other series may be considered in the light of these criteria.

It is important to note that between primary and secondary ores specimens were found where the minerals of the sulphantimonide series had the following order:

Jamesonite.....Boulangerite.....Meneghenite....Geocronite[8]
$Pb_2Sb_2S_5$.....$Pb_4Sb_2S_7$.....$Pb_5Sb_2S_8$

Geocronite is rarely found in the Bottino lode, but it is interesting to connect such chemical facts with the crystallographic

[6] A. D'Achiardi, *Minn. della Toscana*, vol. II., p. 332.
[7] A. D'Achiardi, *Min. della Toscana*, vol II.
[8] Kerndt, *Pogg. Ann.*, Bd. LXV., p. 302, 1845.

forms through which primary ores change into secondary. The writer is convinced that crystals are interesting not only to mineralogists but to economic geologists, who may see in them a means of detecting and studying many chemical changes which would be impossible to follow through the complex chemical reactions which involve the entire transformation of primary ores into secondary.

PRIMARY ORES.

The origin of the fissure vein which forms the tabular mineral mass of the Bottino lode has not been much studied. In the writer's opinion, the lode was the result of fissure filling by solutions carrying metallic elements dissolved from the country rocks. According to another hypothesis, the deposit was formed by magmatic intrusion. This opinion is based on the occurrence of a tourmaline-like rock within the vein.[9] This rock, brown in color, is composed of microscopic needles of tourmaline interwoven with quartz, galena, blende, siderite, pyrrhotite, pyrite and occasionally, at the upper part of the vein, chalcocite.

Chalcocite here is of hypogene origin, like that of the Bristol deposit studied by Alan M. Bateman.[10] Its occurrence in orthorhombic crystals, as at the Frigido mine,[11] is an example of the application to nature of the findings of the Geophysical Laboratory of the Carnegie Institution of Washington.[12] Unfortunately chalcocite is very scanty here, but its occurrence only in the upper part of the vein proves that it was deposited by a solution whose temperature fell below 91° only toward the end of its subterranean travel. It may be interesting to note that no chalcocite was found at the deeper zone even though its isometric forms, which are produced above 91° C., might have been expected. The Geophysical Laboratory investigations do not seem to apply conveniently to nature in this case.

Origin of Primary Ores.—The tourmaline-like rock found within the vein is not a magmatic rock in the writer's opinion.

[9] A. D'Achiardi, "Tormalinolite del Bottino nelle Alpi Apuane," *Proc. Ver. Soc. Toscana Scienze Naturali,* Pisa.

[10] Alan M. Bateman, ECON. GEOL., vol. XVIII., 1923, pp. 122–166.

[11] C. L. Sagui, ECON. GEOL., vol. XVIII., pp. 699–700.

[12] Posnjak, H. E. Merwin, E. T. Allen, ECON. GEOL., vol. X., pp. 491–535.

It is frequently found isolated in lens-shaped masses within the workable part of the deposit, and from its relation to the secondary ores it may be determined to be a primary deposit on which depends, at least partially, the secondary one. That such a tourmaline-like rock was not of igneous nature may be shown by the fact that primary chalcocite crystallized in orthorhombic forms, and still better by the fluid inclusions of the quartz which often completely fill their spaces, proving that no vapor-pressure was present.

At a very deep zone the tourmaline of the crystalline schist was taken into solution by hot underground waters under considerable pressure. The same solution also carried away metals found disseminated in small quantities through the country rock. Later tourmaline and other minerals were deposited; pyrrhotite is more abundant in the deeper zone, whereas pyrite, galena, and zinc blende are uniformly distributed.

As a rule tourmaline is not supposed to be found at the middle and upper vein zone, which is not true in this case. The writer thinks that possibly tourmaline was decomposed at a certain depth into silica, colemanite ($Ca_2B_6O_{11}\cdot 5H_2O$) and other borax minerals by calcium and other carbonates, carried in solution, and reprecipitated upward where favorable conditions were met with. For instance, silica would be taken into solution if ammonia were present. As ammonia and H_2S are found in the emanations of Soffioni from which boracic acid is obtained at Massa Marittima about 100 miles from the Bottino mines, the writer assumes that similar chemical conditions are met with in both zones.

In the Bottino lodes cassiterite (SnO_2) was found as high as 0.2 per cent. The gangue also contains, besides tourmaline, apatite, fluorite, and arsenopyrite, minerals which are characteristic of tin veins. The occurrence of tin is noteworthy, since it is supposed to be an element given out by magmatic emanations which attack the walls, inducing profound metamorphic action. This is not true in this case, as no alterations are found along the rocks of the vein. If we consider that the Bottino vein is only

one of a parallel series, the future possibilities of the region may be imagined, if the modern criteria of economic geology are rightly applied in finding new deposits.

ORIGIN OF SECONDARY ORES.

The most important fact which must be considered in connection with the origin of the secondary ores is that tourmaline, which is by far the largest part of the primary deposit, is not found among the secondary ores, including pyrrhotite and chalcocite. Tourmaline was very probably redissolved by the underground waters which produced secondary deposition; and it was changed into silica, colemanite, other borax minerals, and aluminium, under different chemical forms. As is well known, carbonate waters easily decompose borax minerals, so boracic acid was probably formed in this transformation and carried away.

The largest part of the original primary ores which were changed into secondary is supposed to have been less rich in tourmaline, carrying instead more metallic matter than those considered above. There is little evidence of such a primary ore, but pyrrhotite has been met with in veins ten inches thick where chalcopyrite, blende, galena and chalcocite were disseminated. That such an ore is of primary origin may be inferred from two facts: first, that pyrrhotite occurs and that chalcocite is found with the same characteristics as that of the Bristol and Frigido deposits; second, because the ore is found outside the complex fracture zones within which only the secondary deposits seem to be met with.

In conclusion, the primary deposits formed by tourmaline have not had a preponderant part in the formation of the secondary ores; galena and zinc blende were their principal elements abundantly distributed within the more fractured zones. In the Bottino lode, which was mined to a depth of about 900 feet, the amount of silver diminishes with the depth, while zincblende increases. In the upper part the percentage of silver is about 0.2 to 0.4 per cent., in the middle, 0.1 to 0.2 per cent., and below that still lower, whereas zinc blende is still increasing.

The largest workable shoot at the east side of the vein is interrupted by a fault and workings were thus limited. A long drift of about 400 yards was pushed eastward hoping to find the lost branch of the deposit, but was discontinued.[13] A few years ago the writer studied the problem and by considering the deformation of the foliation planes, due to the stress of the fault, and by taking into consideration the entire fracture zone preceding the fault, the shoot was met with 20 yards over the fault plane. The first ore found was a vein of a few inches of the primary pyrrhotite [14] described above.

It is important to note that secondary copper ores increase in the deeper zone and therefore the percentage in tin is slightly increased, even though the amount is always insignificant. The zonal arrangement is thus evident. It may be surprising not to find here supergene chalcocite, but it occurs as hypogene chalcocite through the primary ores of the Bottino lode.

All these conclusions are of special interest if we consider their coincidence with those drawn concerning the Bristol chalcocite; and in connection with ore deposit investigations they may prove important economically.

[13] F. Blanchard, *Bull. Soc. des Ind. Min.*, I., 1887.
[14] C. L. Sagui, *Bol. Soc. Lunigianese G. Capelluni*, vol. I., p. 174, 1919.

FABRIANO, ANCONA,
ITALY.

THE OCCURRENCE OF VANADIUM AND NICKEL IN PETROLEUM.*

E. DEGOLYER.

THE petroleums, using the term in its widest and most complete sense, are generally considered to embrace the whole series of so-called mineral hydrocarbons occurring in nature, whether in gaseous, liquid, or solid state. They consist not only of a bewildering variety of mixtures of the compounds of carbon and hydrogen, but often also of sulphur compounds, oxidized and nitrogenous substances, etc., whose exact nature and composition is not always clearly determinable, as well as small amounts of many of the rarer elements such as vanadium, nickel, phosphorous, etc.

We know much or little about the chemical composition of the petroleum according to whether one considers what has been accomplished in their examination or what has yet to be done. Ordinary commercial analyses are numerous, but they are strictly what their name implies, and consist usually in the determination of certain physical characteristics such as specific gravity, viscosity, flash point, etc., and the fractionation of the oil according to arbitrarily selected ranges of boiling points as determined by the demands of utility. Sulphur is usually determined and the analysis usually indicates the extent to which asphaltenes are present. Information as to the extent to which specific hydrocarbon compounds or rarer elements are present is almost wholly lacking.

Moreover, if one considers the more detailed examination of the petroleums by some of the leading investigators, such as Mabery and his students, or Richardson, among American chemists, he is impressed by the infinite time and labor required and the paucity of results obtained. Days and months are spent in frac-

* Society of Economic Geologists, New York Meeting, May, 1924.

tionation by repeated distillations of a single oil, and the results are generally qualitative and hardly ever quantitative. Chemists are giving more attention at the present time than ever before to improving the technique of fractionation, and progress is being made, but there is a marked limit to examination even by this tedious proceedure since, beyond certain boiling points, even in vacuum, cracking or decomposition occurs, and new hydrocarbons, which did not exist in the original petroleum, are formed.

The difficulties, therefore, of unravelling any one of the almost infinite number of possible combinations of the hydrocarbons and their associated compounds which make up a single petroleum, give added importance to the consideration by the geologist of the significance of the occurrence of certain metals, even in extremely small amounts, in the petroleums.

The occurrence of elements, other than carbon, hydrogen, oxygen, nitrogen, and sulphur in crude petroleum, is in such minute quantities that it is only within recent years that they have been recognized, and they were apparently first found, as might have been expected, in the asphalts. Kyle [1] described, in 1891, the existence of vanadium in an Argentine asphalt (rafaelite). He found the material, which he described as coal, to yield only 0.63 per cent. of ash which contained 38.22 per cent. of V_2O_5 together with silicates and sulphates of other minerals.

More recently chemists have analyzed more closely the ash from crude petroleums with some surprising results. Hackford [2] states that the ash of Mexican petroleum contains silica, vanadium, nickel, tin, lead, calcium, magnesium, iron, aluminum, sodium, titanium, and even traces of gold. He notes that marine plants have the power of absorbing various elements from sea water and concludes that the occurrence of these elements in the oil favors the theory of the origin of the oil from marine vegeta-

[1] Kyle, J. J., "Apuntes sobre la existencia de vanadio en el carbon de piedra de San Rafael," *Anales de la Sociedad Cientifica Argentina*, vol. 31, Buenos Aires, 1891.

[2] Hackford, J. E., "The Significance of the Interpretation of the Chemical Analyses of Seepages," *Jour. Inst. Pet. Technologists*, vol. 8, pp. 193–213, London, 1922.

tion. His main support for such theory of origin he finds in the high sulphur content of certain algæ—*Macrocystis pyrifera,* of common occurrence in the Gulf of Mexico—and in the high sulphur content of Mexican oils.

The occurrence of certain of these elements in the ash of a crude petroleum is not difficult to explain. It is doubtful whether any of the petroleums examined can be entirely free from impurities, and when one considers that the ash of a petroleum is something like 0.01 per cent. of the whole, it is not surprising that elements of such common occurrence as silica, calcium, magnesium, iron, sodium, and aluminium have been found in small amounts. This is equally true for the asphalts.

A similar explanation may account for some of the rarer elements, but the occurrence of some of the elements such as vanadium and nickel in quantity in petroleums from widely different sources may be a matter of more importance. Vanadium occurs in Mexican oils in such quantities that at one time the possibility of burning coke from Mexican crudes and extracting vanadium from the ash as a commercial proposition appeared feasible enough to receive serious consideration.

The only detailed analysis of a petroleum ash at present available is that by Dunstan [3] for a Persian crude, which is as follows:

Ash, Less than	0.01%
Composition of Ash:	
Fe_2 and Al_2O_3	26.96%
Ca.O	2.31
Mc.O	1.18
V_2O_5	5.03
Ni.O	2.70
Mn.O	4.39
$Si.O_2$	2.29
P_2O_5	5.53
SO_3	35.29

Dunstan's comment upon this analysis is that its most striking feature is the large percentage of nickel and vanadium—two of the most active catalytic agents known in the metallic state.

[3] Dunstan, A. E., "The Crude Oil of Maidan-i-Naftun," *Jour. Inst. Pet. Technologists,* vol. 10, pp. 51–82, London, 1924.

He further notes that the ash exhibits a small degree of radio activity, 15 grams of ash showing about two thirds of the activity of a gram of uranium nitrate when tested by the usual methods.

In discussing Dunstan's paper, J. McConnell Sanders [4] notes that Mexican oil also contains phosphorus.

The analysis of this ash shows high vanadium, nickel, and phosphorus beyond what might be expected if the ash consisted only of earth matter contaminating the oil. It is perhaps unsafe to generalize on the basis of this single analysis and conclude further that the low silica is evidence pointing in the same direction—particularly so since the Maidan-i-Naftun oil is probably produced from a limestone or gypsum rather than a sand, and particularly so in view of the high percentage of sulphate radical.

Hewett [5] has described in some detail the occurrence of vanadium bearing asphalt and vanadium in associated rocks in the Yauli and Quisque districts of Peru and mentions its occurrence in an asphalt from Page, Oklahoma.

Hess [6] has also described the occurrence of asphalts at Temple Mountain, Utah, which contain uranium as well as vanadium. Analyses of two specimens given by him show vanadium content of 0.23 per cent. and 1.17 per cent. and uranium contents of 1.13 per cent. and 2.88 per cent. respectively.

The petroleum investigation of greatest interest, however, among recent investigations, is that recently made by William Ramsay [7] in his examination of various petroleums for nickel.

Ramsey reports that so far, all oils examined have shown the presence of nickel. The detailed results which he reports are as follows, the crude petroleums examined being partially distilled oils of the type of fuel oils or Diesel engine oils:

[4] Mr. McConnell Sanders states that a very sensitive test for phosphorus consists in heating the organic substance containing it on a polished glass rod. Even minute quantities can be detected by the corrosion of the glass surface of the rod.

[5] Hewett, D. Foster, "Vanadium Deposits in Peru," *Amer. Inst. Min. Eng. Trans.*, vol. XL., pp. 274–299, New York, 1910.

[6] Hess, Frank L., "Uranium-bearing Asphaltite Sediments of Utah," *Eng. and Min. Jour.-Press.*, vol. 114, pp. 272–276, New York, 1922.

[7] Ramsay, Wm., "The Significance of Nickel in Petroleum," *Jour. Brit. Inst. Pet. Technologists*, vol. 10, pp. 87–91, London, 1924.

Source.	Consistency.	Ni parts per million.
Mexican	Semi-solid	83
Mexican	Thick	49
Mexican	Medium	67
Texas	Medium	44
Texas	Medium	71
Texas	Thin	68
Californian	Medium	49
Californian	Thick	63
Roumanian Ostatki	Semi-solid	17
Persian	Medium	12
Persian	Thin	93
Persian	Thin	4
Burmah	Thin	12
Burmah	Medium	8
Java, Surabaya	Thin	3
Borneo, Balik Pappan	Thin	1
Borneo, (Mixed)	Thin	3
Asphalt, Trinidad		194
Asphalt, Swiss		120
Asphalt, rock (unknown)		14
Gilsonite, California		133
Petroleum pitch, U. S. A.		240
Ozokerite (Germany ?)		trace
Ozokerite Refined German		nil

He states that it is noteworthy that the more asphaltic oils, as a rule, carry most nickel, and that the asphalts are comparatively rich in it. He further notes that attempts to ascertain the condition in which the nickel exists in the oil have, so far, proved abortive, but that there are indications that it may be colloidal, in which case it would act as a powerful catalyst.

Ramsay's theory as to the significance of the nickel in petroleum is that it acts as a catalytic agent and would permit the formation of hydrocarbons by the hydrogenation of carbon, carbon monoxide, or even carbon dioxide, thus providing a plausible, or at least possible, method for the inorganic origin of oil. He cites a theory of Sabatier and Senderen's to the effect that petroleum might be formed by the hydrogenation of carbon or carbon compounds, and concludes that his discovery of the common occurrence of nickel in petroleum is substantial evidence favoring this theory of origin.

Too much evidence favoring the theory of organic origin of petroleum has been developed within the past few years to allow the acceptance, at the present time, of this theory of inorganic origin, but the common occurrence of nickel in petroleum of widely different chemical types and geographic sources suggests that its presence may have an important bearing on the origin even from organic material.

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NEW YORK CITY.

DISCUSSION.

Mr. Steiger: There are several criticisms which may be made of the analysis of E. DeGolyer's paper. Even if iron were not quantitatively determined (which is but little extra work) whether the bulk of the 26.96 per cent of $(FeAl)_2O_3$ is iron or aluminum might easily have been stated by the analyst from a simple observation of the color of the precipitate. This information is important in any interpretation of the analysis. In balancing the atomic ratios, there is, even after combining all Ca, Mg, Ni, and Mn as sulphates, considerable SO_3 remaining which must be combined with iron and aluminum. Both iron and aluminum sulphates are easily decomposed at the temperature and by the long ignition which must have been used to burn the ash free from carbon. The summation of this analysis is only a little more than 85 per cent. Some idea should have been given as to the remaining 14 or 15 per cent. If this happens to be composed of the alkalis, it may in part account for the large content of SO_3.

Mr. DeGolyer is undoubtedly justified in recommending that the organic theory be retained for the present, but from the fact that nickel carbonyl is an easily volatile compound, and also that vanadium is known to be easily volatilized, the presence of these two metals in hydrocarbon metals certainly strongly suggests their inorganic origin.

E. T. Erickson: The term "petroleum" used by the author to include "the whole series of so-called mineral hydrocarbons occurring in nature, whether in gaseous, liquid, or solid state" is given the same meaning generally understood in the use of the terms bitumen and pyrobitumen.

"The term bitumen[1] in a generic sense includes the varied types of petroleum and hydrocarbons, either natural or artificial, *i.e.*, oils, asphalts, resins, mineral waxes that are soluble in neutral solvents such as

[1] Detecting small quantities of petroleum, E. T. Erickson, *Eng. & Min. Jour.*, July, 1921.

chloroform, carbon disulphide, carbon tetrachloride and like substances." The term pyrobitumen is used to include the naturally occurring solid organic substances of a hydrocarbon nature that are insoluble in the above solvents but which will yield bitumens artificially upon distillation.

Clifford Richardson [2] restricts the meaning of the term petroleum as a particular form of bitumen. A similar restricted meaning is given by Hofer [3] in which the term is applied to bitumens subclassified of a fluid nature.

Mr. Nason: The above paper interested me since, under commission from the United States Steel Corporation, I spent nearly two years in the study of vanadium deposits in the United States and in Mexico.

With little detail, the following are facts. What to do with these, I do not know. I found vanadinite associated with deposits of lead-zinc-silver mines and prospects in New Mexico, Arizona and Old Mexico. In both countries the vanadium seemed to be confined almost, if not quite, exclusively to arid regions, not reaching into well watered districts. The vanadium, I concluded, decreased with depth. The deposits were exclusively veins. From New Mire, Colorado, vanadiferous sandstones can be followed from the above locality and more or less continuously, into the carnotite fields of Dolores County and thence into eastern Utah. The element is supposed to be in the form of roscoelite. In the New Mire district, even where the sandstones are colored a bright green, the percentage of vanadium is extremely variable.

Above New Mire, on the Bear Creek Mesa, thin, irregular beds of coal are found. These coals contain from 0.05 per cent. to 0.1 per cent. V. The Mesa is about 1500 feet higher than the sandstones near the level of the San Miguel river. In this connection it may be interesting to note that analyses of coals from the Richmond Basin show practically the same amount of V.

Carboniferous coals from the central, eastern and southern states also carry about the same amount of V.

In the state of Nuevo Leon, Mexico, on the Rio Blanco, a coal bed or seam, carried 85 per cent. fixed carbon, 10 per cent. volatile and 5 per cent. ash. The ash showed about 25 per cent. V_2O_5. This coal is about as vanadiferous as the San Rafael coal in Argentina. Bitumens from Utah and anthraxolites from Ontario showed hardly a trace of V.

The above localities, including the silver-zinc-lead deposits, are in the younger geological formations. These may or may not be connected with intrusive rocks. Among unquestioned igneous rocks an extensive

[2] Characterization and Differentiation of native Bitumens and their Residuals: *Jour. of Ind. and Eng. Chemistry*, vol. 5, No. 6, June, 1913.

[3] H. Hofer-Heimhalt, Das Erdol und seine Verwandten (vierte neubearbeitete auflage; 1922).

area north of Socorro, New Mexico, yielded on a 1500 lb. sample an average of 0.15 per cent. V. The gabbros of the Adirondacks and other gabbro areas in the United States (Joseph T. Singewald, Jr., Titaniferous Iron Ores of the United States) and the titaniferous iron ores give from 0.20 per cent. V to 0.65 per cent. V (from personal sample from near Greensboro, N. C.). The concentrates (magnetic) yielded about 65 per cent. Fe, Ti about 1 per cent., with V, 1.3 per cent. The Adirondack gabbro iron ores yield, crude, from 0.20 to 0.61 per cent. V_2O_5. Invariably, in magnetic concentration, the vanadium increases with the magnetite and decreases in the titaniferous tails. The inference, if not an actual fact, is that the vanadium is associated with the magnetite component and not at all with the titanium. The gabbro rocks are also invariably titaniferous. Among the rocks associated with practically titanium-free iron ores, not only are the rocks free from titanium, except as titanite, but the ores themselves carry only from 0.05 to 0.1 per cent. Ti. Even this titanium may be in the form of sphene. So far as I know this point is undecided. At any rate, in the rocks carrying the titanium-free iron ore, the origin of both rocks and iron ores is, as yet, an unsettled question; that is igneous or sedimentary.

One investigating the occurrence of vanadium can consult with great advantage "The Data of Geochemistry," by Frank Wigglesworth Clarke. In the above volume, pp. 712–714 incl., references show that vanadium is found in ashes of woods, of peats and of other forms of organic life.

A search of the available literature will show that vanadium is a widely distributed element and that, so far as actual presence is concerned, except in the case of the titaniferous iron ores, it shows no preference either for igneous (inorganic) or sedimentary rocks, including living flora.

D. F. Hewett: I am very much interested in this summary. Also, I am sorry that F. L. Hess of the Geological Survey is not here, as he has a comprehensive record of the occurrence of vanadium and nickel in petroleum and related substances. In order to make the record more complete, I might refer to recent chemical work on Argentine petroleums. E. Longobardi and N. Comus in 1911 published analyses of petroleum from four fields in Argentina with the following results:

San Rafael field, 100 grams yielded .0045 grams vanadic oxide.

Comodoro Rivadavia field, 100 grams yielded .000246 grams vanadic oxide.

Sierra Latena field, 100 grams yielded .000317 grams vanadic oxide.

Tartagal field, 100 grams yielded trace vanadic oxide.

I am not ready to agree that the presence of nickel and vanadium in petroleum indicates its inorganic origin. During recent years considerable analytical data have been accumulated concerning the amounts of

many elements in living organisms and these should be adequately considered in speculations about the origin of such elements. For instance, it is known that certain varieties of Holothurians (sea-cucumbers) contain unusually large percentages of vanadium. It is not known, I believe, how far high metal content in organisms is fortuitous or how far essential to its existence. The facility with which certain vanadium oxides oxidize and reduce, indicates that it may play somewhat the same part in the blood or circulatory system as iron does in the human system.

EDITORIAL

THE PITCH OF ROCK FOLDS.

In the customary instruction in elementary geology as provided by means of lectures and text-books, an account is given, as a matter of course, of the folding of beds of rock under the influence of tectonic pressures with the production of anticlines and synclines. Commonly it is assumed that the axes of folding are horizontal, and frequently no reference is made to this point. In consequence too little attention appears to be given to the fact that the fold axes are not infrequently inclined to the horizontal, that is to say they pitch, the angle of pitch being the angle of inclination measured from the horizontal. The purpose of this article is to draw attention to the importance, both scientific and economic, of including observations of the angle and direction of pitch, or, more briefly, the pitch, of rock formations amongst the data to be recorded in field work, wherever opportunity offers.

Pitch phenomena are as a rule most apparent in the oldest and most folded rock, the Archæan, the reasons for which will appear later. But hitherto greater attention has been devoted to these phenomena in younger formations, particularly those that carry petroleum. In this group of cases the pitch of the fold axes is frequently but a few degrees, and is usually detected by the careful mapping of the outcrops of successive beds of rock. But the economic importance of a knowledge of the angle of pitch in such cases is often extreme: for in the absence of faults it is obvious that the movements of such a mobile mineral as petroleum will be finally guided by the pitch, so that upon a knowledge of the pitch may depend the selection of the best sites for drilling upon an anticline suspected to carry oil.

But it is in the Archæan rocks that pitch phenomena become the most apparent, partly because the angles of pitch are often

high—up to 90° ; partly because the application of tectonic pressures has been more intense; and partly because the rocks at the time of their last important compression were at a temperature high enough to ensure sufficient molecular mobility for mineral rearrangements to occur and thus preserve a permanent and intimate record of this compression. In the Chhindwara-Nagpur tract of the Central Provinces of India the Archæan gneisses and associated metamorphosed sediments are complexly folded; but this folding when analysed proved to be referable to two main systems. There is first the primary folding that has thrown the rocks into broad anticlines and synclines, often isoclinal, traceable for miles across country, with but small angles of pitch, comparable to those of the Tertiary oil-bearing rocks of Burma.

Subsequently a second set of pressures has acted on the rocks from an entirely different direction, causing a crumpling and puckering of the already folded and tilted strata along axes at an angle to the earlier fold axes. These later folds are sometimes of considerable amplitude and great intensity, and at other times are only of minor importance taking the form of small-scale puckering, with the puckers pitching down the bedding planes, usually askew to the dip. In addition to these folds, large and small, the rocks usually show a grooving parallel to the pitch, and those rocks that are mineralogically streaky or foliated, such as biotite-gneisses, show a streaky arrangement of the minerals parallel to the pitch, indicating a mineral rearrangement under the influence of the later set of pressures.[1]

From the above it will be understood at once what an excellent index to the local pitch is provided by these grooves and streaks, and how to anyone attempting to unravel the structure of the Archæan rocks it becomes as important to observe and record the pitch phenomena as it is to record the dip and the strike. In some cases, indeed, the folding is locally so complex that it is not possible to record more than the pitch. In other cases it is only

[1] Such streakiness has been referred to as "linear foliation," but this phrase appears to be a contradiction in terms.

a study of the pitch that reveals whether a certain structure in isoclinally folded rocks is an anticline or syncline.

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It is not to the scientific worker only, however, that the observation of the pitch phenomena in the Archæan rocks is of importance. Any mineral deposits enclosed therein have, if syngenetic in origin, necessarily been subjected to the same tectonic influences as the enclosing rocks, and, if epigenetic, their deposition has in many cases been guided by the rock structures.

As a good example of the former case mention may be made of the well-known manganese-ore deposits of the Central Provinces of India. These are of syngenetic origin bedded with the enclosing schists and gneisses. They have consequently participated in all the folding movements to which the latter have been subjected, with the result that the manganese quarries and mines afford now magnificent material for the study of pitch phenomena. Had these phenomena been earlier understood from the study of surface data of the type already referred to, it is probable that development work would have been in many cases differently planned. As it is the structure has slowly controlled the situation, and the workings are found to be gradually conforming to the pitch.

As an example of epigenetic ore deposits influenced by pitch the gold deposits of Kolar in Mysore may be cited, though perhaps with a little doubt. Judging, however, from a paper by Mr. T. Pryor read recently before the Institution of Mining and Metallurgy, London, and the discussion thereon, there is, in the Kolar Gold Field, a case of auriferous quartz occurring in shoots that pitch at approximately the same angle and in the same direction as secondary folds or puckers in the enclosing hornblende-schists. Both the quartz and gold are considered to be of later age than these folds, so that there is here, probably, a case of ore-deposition controlled by pitch. The pitch now controls the direction of development work in the mines.

Reference may also be made to the deepest mine in the world, the Morro Velho gold mine in Brazil, where again the ore-deposition and consequently the direction of work appear, judging

from such published data as are available, to have been controlled by the pitch of the rock folds.[2] Many other cases will doubtless occur to the reader.

As the pitch phenomena in the old Archæan rocks date from the period of last intense application of tectonic pressures, it seems obvious that any unrelieved strains that there may now be within the rocks—apart from those attributable to subsequent faults—should have a distribution parallel to the pitch. One is therefore tempted to suggest that the troublesome rock-bursts so frequent in the Kolar mines would if studied spatially prove to have a distribution related to the pitch.

L. L. FERMOR.

[2] T. A. Rickard, *Trans. Inst. Min. Met.*, XXIV., p. 22 & Plate VI.

DISCUSSION AND INFORMAL COMMUNICATIONS

STRUCTURAL AND STRATIGRAPHIC DATA OF NORTHEAST TEXAS.

Sir: In reading Mr. F. Julius Fohs' and Mr. H. M. Robinson's interesting paper on "Structural and Stratigraphic Data of the Northeast Texas Petroleum Area, printed in this Journal, pp. 709–731, Vol. XVIII, Dec., 1923, we find these statements:

> The use of the term "Balcones" should be restricted, however, to the zone of faulting extending east-west for a width of five to fifteen miles, and north-south from San Marcos northeast through Rockwall County, and southeast from San Marcos to Uvalde and Del Rio. . . .
>
> Lahee and Pratt, following Hill, have indicated a broader usage, including the Mexia and Palestine fault zones, where we consider these distinct or sub-parallel zones though related both in origin and age. While some of the shale-sand covered areas intervening between these zones may contain other zones of faulting or individual faults, it is doubtful that such occurrences are sufficiently marked to warrant the inclusion of the whole as one zone. The absence of material faulting between the Mexia and Balcones zones is, in our opinion, proven by the absence of connate Woodbine water west of the immediate vicinity of the east fault of the main Mexia zone.

Mr. Fohs refers here to our joint paper on "Faulting and Petroleum Accumulation at Mexia, Texas."[1] Neither Mr. Pratt nor myself intended to create the impression which Mr. Fohs obtained in reading our paper. Our words relating to this subject ran as follows:

> If the position of the principal known faults around the margin of the Gulf of Mexico be indicated even roughly on a map, . . . the Mexia

[1] American Association Petroleum Geologists, Bull. VII, pp. 226–236, May–June, 1923.

fault immediately becomes an integral part of a larger fault system. This system is dominated in Texas by the Balcones fault zone . . . throwing the younger flanking sediments down on the south and east (p. 228).

The Mexia fault has the appearance from its position and trend . . . of a possible en echelon extension of the Balcones. . . . But the Mexia fault, in its net effect—for the Mexia fault, like the Balcones, is a zone of faulting rather than a single fault—lifts the rocks on its eastern side, whereas along the Balcones, as has been stated, there is a drop on the east. That is to say, if the Mexia fault is in reality an extension of the Balcones, the local stresses which dropped the beds to the east along the Balcones not only die out to the north, but have been reversed still farther north, where they actually lift the beds on the east side of the Mexia fault.

Moreover, the Mexia fault, or a zone of similar faults with upthrow on the east, continues to the south-southwest parallel to the Balcones where this fault is itself strongly developed. Obviously in this region the Mexia fault does not replace the Balcones.

As a matter of fact, briefly stated, both the Mexia line of faulting and the Balcones, as well as the faults in Mexico farther south, are clearly related in origin to a single general cause, namely, the persistent sinking of a great geosyncline or negative element of the earth's crust, the position of which is marked today by the Gulf of Mexico. Intermittently, throughout a large part of geologic time, sediment has been poured into this basin. This load will have tended always to sink and slip away from the margins toward the center of the basin, and marginal faults like the Balcones, with a drop on the basin-ward side, would result from such a tendency. But this sinking and downward slipping at the margins of the basin undoubtedly results in consequent buckling and upward reaction farther out in the basin. Concrete evidence of such upward movement is to be seen in the lines, along which plugs of salt, or salt domes, have been forced upward from deeply buried salt beds in the central parts of the basin. Due to the same reacting forces, perhaps, the line of faulting on which Mexia is situated, lying out in the basin from the marginal downward slips along the Balcones, raises beds east of it to an elevation above their normal position. . . .

The second paragraph quoted above from our article is unfortunately somewhat obscure. It was not meant to imply that we classed the Mexia faults in the Balcones fault zone, but rather that the Mexia fault zone appears to become more strongly developed northward as the Balcones zone grows weaker.

We think that the other quotations are sufficient to indicate that we regarded the Balcones fault zone as distinct from the Mexia fault zone, and that in no sense did we consider the Palestine fault zone as part of the Balcones zone. With Mr. Fohs we agree that there are three separate pronounced zones (the Balcones, the Mexia, and the Palestine) in each of which there has been excessive faulting. Each differs from the others in many of its conspicuous features. All are surely interrelated in respect to the general regional causes and conditions of their origin.

F. H. LAHEE.

GEOLOGY OF THE SUDBURY NICKEL DEPOSITS.

Sir: In the March number of ECONOMIC GEOLOGY there is an interesting account of the Sudbury ore deposits by Messrs. Wandke and Hoffman, who reach the conclusion that the ore bodies have resulted from the replacement of rock forming minerals by hot solutions. Their discussion of the subject is in many respects excellent and they have evidently studied the chief mines and their enclosing rocks very carefully; but it is equally evident that they are unfamiliar with the general geology of the nickel region and that they have missed entirely some of the most important points. In this respect they are like certain other recent writers on the Sudbury ores. They seem unaware that the mines and their vicinity are the worst places in which to work out the geological relations, since there one finds the greatest modifications of the original conditions.

As the Sudbury nickel mines are the most important in the world the origin of these great ore bodies is of interest to the mining geologist and it seems worth while to go over the ground briefly again to show why all the geologists who have been actually engaged in mapping the Sudbury nickel region have become adherents of the magmatic theory of the formation of the deposits.

That famous pioneer geologist, Robert Bell, who was the first to work in the field, suggested that the diorite, as the norite was

then called, was the source of the ore. Later T. L. Walker showed that the norite associated with the ore passed into micropegmatite, proving that there was segregation in the magma, and also that the arrangement of the different phases was reversed in the northern and southern nickel ranges.

Not long afterwards Frank Adams argued for the magmatic origin of the ore deposits, comparing the relationships with those shown by Vogt for the Scandinavian region. He was followed by Barlow who mapped part of the norite boundary and was convinced of the magmatic source of the ores.

While Barlow was still at work in the region the present writer was instructed by the Bureau of Mines of Ontario to prepare a complete map of the nickel ranges. As a recent student of the Bergakademie at Freiberg, where the aqueous origin of ore deposits was taught and magmatic segregation not mentioned, I came to the work rather prejudiced against the theory of my predecessors.

My own work lasted several summers and resulted in the discovery that the nickel ranges were really parts of the outer edge of a great spoon shaped or boat shaped basin of norite passing up into micropegmatite, as Walker had foreshadowed.

The outer, or basic, edge of the sheet was followed without a break, except where drift covered, around the whole basin, which was 37 miles long and 17 wide. During the years of this field work certain interesting features were disclosed.

Passing outward from the interior of the basin toward the lower, or basic, part of the sheet one usually noticed that there were rusty spots in the norite, often widely scattered, and that these grew in numbers as the edge was approached until the actual margin was often covered with a band of gossan which could be followed hundreds of yards or even for a mile or more.

This " pock-marked " character of the lower edge of the norite became our best field evidence in separating the eruptive sheet from similar dark greenish gray eruptives adjoining it, since the latter were free from the rusty spots.

It was observed, however, that where the boundary of the

norite had an important inward bend the rusty spots were fewer in number or ceased altogether. On one stretch of about six miles of the northern range, where there was a broad incurving of the norite edge, no gossan was found and the prospectors had taken up no claims. Here the rock proved to be intermediate between norite and micropegmatite, and the typical norite appeared not to have reached that portion of the edge.

On the other hand it was found that outward bends of the norite margin were more heavily charged with ore, and that most of the important mines were at or just beyond such outward bays in the country rock. It was further found that the width of the nickel eruptive sheet had an important bearing on the size of the ore bodies. In a general way the large deposits were where the norite-micropegmatite band was wide; and the six mile strip without ore on the northern range was the narrowest part of all.

It was estimated that the greater part of the ore existed as blebs disseminated through the basic edge of the norite, the workable bodies of solid ore containing much the smaller amount of the sulphides of the region. It was found that at the great Creighton open pit (in the early days) the margin of the ore against the foot wall was fairly sharp but the margin toward the norite was indefinite. In practice the inner boundary was determined by assay, pyrrhotite-norite with less than about 3 per cent. of nickel and copper being left unmined.

A study of the ore of the Frood, or No. 3 mine, showed that many thousands of tons which were mined and smelted consisted of pyrrhotite-norite with hardly any solid ore. Carloads of such ore were seen by the members of the Geological Congress in 1913 and typical specimens of pyrrhotite-norite were collected without trouble. More than one third of the known ore reserves of the Sudbury region is included in this mine.

During the field work some hundreds of thin sections were made and it was found that in most places the norite was a good deal weathered, the hypersthene and often the pyroxene having been changed to uralite or hornblende. It was noted with surprise, however, by Walker, Barlow and myself that some of the

freshest rock was near the Creighton and Murray mines; and that in some thin sections of pyrrhotite-norite thickly charged with ore the hypersthene, the most susceptible mineral of all, was perfectly fresh.

It was found that fresh or weathered pyrrhotite-norite occurs at every ore deposit, whether marginal or offset, confirming the prospector's idea that if there was no "diorite" there was no ore.

It was found that except along some parts of the southern range the norite with its disseminated ore dipped rather gently inwards toward the centre of the basin. This is specially well seen near the two ends of the basin; but is less evident near the great ore bodies of the central part of the southern range, where there has been a great deal of faulting, obscuring the relationships. At many of the outlying parts of the ranges, as near the Sultana mine on the west and the Whistle mine on the northeast, the old floor of country rock has been disclosed by the weathering of the norite, and patches of pyrrhotite-norite or of solid ore are found for a hundred yards or more up the slope, lying especially in small depressions of the underlying floor.

It was noticed, too, that the solid ore of the marginal mines, such as the Creighton and Murray, contained sharp-edged fragments of the country rock, proving crushing and readjustment of the enclosing rocks, but no gangue minerals, such as quartz or calcite. These ores showed no banding nor crustification such as might be expected if circulating water had deposited them. Morever the enclosed rock fragments were no more altered than the wall rocks; there was no sign that they had been attacked and their minerals replaced by ore.

It was found, however, that the offset deposits were considerably modified, where the ores had wandered some distance from the edge of the norite; and that they contained secondary minerals indicating that water had played a part in their formation and rearrangement.

One important additional feature impressed the geologists who mapped the region; the simple and monotonous character of the ores. Everywhere, in pyrrhotite-norite, marginal deposits and

offsets, one found just the same three sulphides, pyrrhotite, chalcopyrite and pentlandite, in about the same proportions, except that there was more of the copper ore in the rockier mines and that two or three of the narrowest offsets contained some arsenides.

The ores were as uniform as the norite with which they were associated; they were the same whatever the character of the country rock, which might be at one place or another Laurentian granite and gneiss, very acid granites of later age, very basic norites, green schist, graywacke or quartzite.

The making of the map convinced me and my assistants that the norite was the source of the ore and that the ore was contained in the original magma; otherwise one could not account for the vast quantity of sulphides enclosed as small separate blebs in cubic miles of norite. Careful study proved that these little masses of ore, exactly like the solid ore of the mines, were completely enclosed in the eruptive rock with no suggestion of shearing or crushing to provide channels for circulating water. Such enclosures occurred in perfectly fresh norite and the ore must have been present when the magma cooled and the rock minerals crystallized. They were often very thinly scattered for hundreds of yards or even half a mile away from an ore body. Our thin sections of fresh pyrrhotite-norite usually show no tailing out of ore suggesting its later introduction, and its relation to the dark minerals of the rock is much the same as that of the magnetite which is found in most thin sections.

Since all of the ore bodies occur at or near the lower edge of the norite-micropegmatite sheet and most commonly in downward bends of the country rock; and since the molten sulphides are much heavier than the molten rock, it was inferred that the separation of the ore was largely due to gravitation.

The evidence outlined above applied to nearly all of the circumference of the sheet of norite-micropegmatite, but for three miles along the southern side of the norite toward the eastern corner of the basin the edge was drift covered. It was sug-

gested that ore deposits might be concealed here. They were found by diamond drilling a few years later.

Details of the geological study and mapping of the nickel region may be found in a Report of the Bureau of Mines of Ontario (vol. XIV., Part III., 1905); and in The Nickel Industry published by the Canadian Department of Mines, Ottawa, 1913.

Since that time the mines have been greatly developed, many interesting details have been discovered, many articles have been published in regard to the origin of the ore deposits, and the writer has several times revisited parts of the region, but the main conclusion that the ore is due to magmatic segregation is unshaken. The theory should, however, be widened along the lines suggested by Howe[1] and Bateman,[2] to include the coming in of molten ore along certain channels after the norite had partially consolidated. This ore always contains minerals belonging to the norite and must have been the result of magmatic segregation from the eruptive sheet, although it has wandered more or less from its original point of separation.

Having briefly stated the case as viewed by all the field geologists who have mapped the region, one comes back puzzled to find careful workers, such as Wandke and Hoffman, and at an earlier time Knight, taking an exactly opposite view and accounting for all the phenomena by hydrothermal means!

The only explanation seems to be that these gentlemen have confined their observations so closely to the mines and their immediate surroundings, that they have overlooked the broader evidence. This is specially surprising in regard to Wandke and Hoffman since they were working at the Creighton mine, which in earlier days was considered to afford the best evidence of segregation.

A visit to the Creighton last spring accounted for their attitude to some extent. Though the mine was originally a typical marginal deposit it has gradually changed in depth into an offset deposit. In the lowest workings the ore is completely enclosed in

[1] Howe, Ernest, ECON. GEOL., vol. IX., 1914, pp. 503, etc.

[2] Bateman, A. M., ECON. GEOL., vol. XII., 1917, pp. 391, etc.

the country rock and does not touch the edge of the norite. The hanging wall of the great open pit, which was formed of very fresh pyrrhotite-norite, has entirely collapsed, removing the evidence of transition from ore to norite which was so striking when it was first opened.

But how do Wandke and Hoffman account for the vast amount of pyrrhotite-norite still remaining within sight of the mine? They themselves say "throughout the differentiated igneous body there are small blebs of sulphide. . . . This basic rock with its spots of sulphide is, however, in no sense to be regarded as ore, for the sulphides constitute less than one half per cent. of the rock. At the Creighton mine such a zone of spotted quartz norite, six hundred yards wide and three quarters of a mile long, occurs several hundred feet distant from the contact. Here again, this zone is in no sense to be regarded as ore."

Although from the miner's point of view this pyrrhotite-norite with only half a per cent. of sulphides is not ore, the total quantity of sulphides contained in it, taking their own estimate of dimensions as correct, is enormously greater than the amount of ore in the mine.[3]

Now these small masses of sulphides are completely surrounded by rock. Thin sections of this pyrrhotite-norite in the collection of the University of Toronto show no fissures through which the sulphides could enter the rock after consolidation. In some of the sections even the hypersthene is perfectly fresh, there are no secondary products and the sulphides are enclosed by the usual minerals of the rock just as the magnetites are. In the field it is found that these little round spots of sulphide are often widely separated, a bleb or two in a cubic yard. They are as much an original constituent of the rock as the magnetite or apatite found in thin sections and they must have segregated out of the cooling magma in the same way as the other minerals.

As the blebs of sulphide are of exactly the same materials as the ore of the mine to say that they are not ore and therefore do not need to be accounted for is merely shirking the most important

[3] ECON. GEOL., vol. XIX., 1924, p. 200.

problem in the genesis of the nickel deposits. It is rather curious to find them referring to the similar rock at the Frood mine, of which many thousand tons have been mined and smelted, as ore, in spite of the fact that it is largely a dissemination of "eyes of sulphide in basic rock."[4] They add that "these blebs at once recall the grains of sulphide in certain phases of the main nickel eruptive, and in the hand specimen the ore suggests that sulphides and silicates were formed contemporaneously." They believe that the Frood rock is quartz diorite and not norite; but my own set of rock sections shows every transition between typical fresh quartz norite and this rock in which the hypersthene and augite are changed to hornblende. There is no doubt in my mind that the Frood pyrrhotite-diorite is a somewhat sheared and metamorphosed pyrrhotite-norite; but in any case it will hardly be denied that this sulphide-bearing rock has sprung from the same magma as the main body of norite and must be taken into account in solving the problems of the region.

The Frood has much the largest reserves of ore of any mine in the Sudbury district; and if one includes its 45,000,000 tons with the vast amounts of pyrrhotite-norite near the Murray, the Creighton and other mines it is obvious that by far the greater part of the nickel and copper minerals of the region is enclosed as small separate blebs in the marginal parts of the norite or its offsets and not in the solid ore bodies of the working mines.

A careful re-reading of the article of Wandke and Hoffman shows no attempt to account for this extraordinary arrangement of pyrrhotite, pentlandite, and chalcopyrite in distinct blebs scattered through many millions of cubic yards of norite and containing most of the sulphides of the region. Their elaborately worked out paper accounts only for the present relationships of the ores found in the working mines but not for the original source of the ores. The most important problem of all they do not touch, or perhaps even recognize, because they are so engrossed with the secondary changes displayed in some of the mines.

[4] *Ibid.*, pp. 193–4.

A theory which leaves unexplained the largest part of the known sulphides and considers only the changes and rearrangements to be found in the prominent mines does not adequately cover the ground, though its presentation is of use as calling attention to hydrothermal phenomena which have played a late though somewhat important part in completing the ore bodies as we now find them.

On the other hand the theory of the magmatic segregation of a very minute percentage of sulphides out of a vast sheet of eruptive rock slowly cooling under a thick blanket of sediments gives a reasonable starting point for the whole series of phenomena observed. The heavier materials, norite and ore, tended to settle to the bottom, leaving the lighter granitic portion to cool near the top of the sheet. The sulphides were mostly trapped as tiny blebs in the lower part of the crystallizing norite magma, like shots of matte in slag, as suggested by the metallurgist, David Browne; but a smaller part of it escaped into pools in the depressions below the norite. A great amount of settling and faulting took place in the enclosing rocks, which were often shattered and fissured, as can be seen near the great mines of the southern range; and in this process a portion of the still liquid sulphides came under pressure and was forced into fissured or brecciated zones. Its easiest mode of escape was in the hollows under the partially solidified mixture of norite and ore, where it acted like an eruptive, carrying with it blocks of country rock, and filling all the available openings. This is the process suggested by Bateman. As the final cooling proceeded hot magmatic waters or vapors acted to some extent upon the minerals of the rocks and the ores themselves.

This outline of the course of events seems to provide a logical explanation of the facts as one finds them, not alone in the ore deposits, but on the broad scale as affecting the relations of the nickel eruptive as a whole.

The literature in regard to sulphide deposits of magmatic origin is extensive but need not be recalled in detail. A good outline of it is given in F. S. Hudson's very interesting account of the

Cuyacama Region of California,[5] where deposits very similar to those of Sudbury occur with norite and are accounted for as syngenetic or magmatic.

Among the later publications, one of the most judicial and important is Bateman's discussion of the question.[6] He follows up Howe's suggestion[7] that the differentiation of sulphides from silicates took place in the magmatic reservoir and not in the laccolithic chamber and that the sulphides were intruded after the norite had cooled. As has been mentioned before, it is probable that this occurred to a certain extent and was of importance in regard to some of the great ore deposits, though not accounting for others nor for the pyrrhotite-norite.

Bateman had spent only a brief period in the region when his paper was written but had studied the literature, and thin and polished sections, and he attempts to harmonize the conflicting theories. He suggests finally that the workable deposits were formed "only in minor part by magmatic segregation *in situ* from the nickel eruptive." He was evidently not aware that the largest of the deposits, the Frood, consists mainly of pyrrhotite-norite.

In the same year J. H. L. Vogt published an admirable study of Die Sulfid: Silikat-schmelzlösungen,[8] in which he describes experimental work on the solution of sulphides of the metals in silicates, and then discusses the nickel deposits associated with norite and other rocks, paying much attention to the Sudbury relationships.

It is not easy to see how any one reading his detailed account of the relations of sulphides to eruptive rocks, as illustrated by the results of his experiments on artificial silicate sulphide melts, can resist his conclusion that the ore bodies and the pyrrhotite-norites are of magmatic origin. From his study of the Scandinavian deposits he draws the same conclusion as was reached by

[5] Univ. Cal. Pubs., vol. 13, No. 6, pp. 175–252, 1922.
[6] Econ. Geol., vol. XII., 1917, pp. 391–426.
[7] *Ibid.*, vol. IX., 1914.
[8] Norges Tekniske Hoiskoles Geologiske Institut, Meddelelse, No. 7.

myself at Sudbury, that the volume of ore in the individual deposits has a relationship to the amount of norite with which it is connected.

Vogt's later publication under the same title, which appeared in 1919,[9] while of great theoretic interest, is mostly confined to an account of his investigation of slags, but does not touch directly the occurrence of ore deposits in nature. His account of *" die mechanische beigemingten Steinpartikelchen in den Rohschlacken,"* with its illustrations,[10] shows exactly how the pyrrhotite-norites originated.

Probably the most original, as well as one of the most important contributions to the discussion of the origin of the Sudbury deposits is that of Hugh M. Roberts and Robert Davis Longyear.[11] The Longyear Company carried out a campaign of exploration for nickel-copper ore in the Sudbury District in 1916 and 1917. The work was done mainly by diamond drilling, and a large body of ore was found near the northeast corner of the eruptive sheet beneath a thick covering of drift materials. The ore body is 7,500 feet long, the longest in the district, and is of the marginal type, lying between pyrrhotite-norite and the underlying quartzite or greenstone; and it occurs at a point where it had been suggested in the Nickel Industry that ore might be looked for.

The Longyear Company were wise enough to have careful geological and petrographical work carried out in connection with the exploration, and the conclusions reached strongly support the theory of magmatic segregation. They found that " the norite wall is always spotted with blebs of sulphides. The spotted norite passes by insensible degrees into barren norite containing practically no sulphides." [12] The paper concludes with " The point we have tried to make clear is that the domi-

[9] " Die Sulfid: Silikat Schmelzlösungen, Utgit for Fridtjof Nansens Fond," Kristiania, 1919.

[10] *Ibid.*, p. 103, etc.

[11] " Genesis of the Sudbury Nickel-copper Ores as Indicated by Recent Explorations," *Trans. Am. Inst. Mining Engineers,* 1918.

[12] *Ibid.*, p. 583.

nant factor controlling the deposition of the Sudbury ores is magmatic segregation *in situ*. Hot solutions may have been active, but only served to influence the local character and position of the ores."

They call attention to the volume relations of the norite and sulphides which supplied the reason for their exploring at the northeast corner where the ore body was found.

There is only one small point in their admirable paper which may be somewhat criticized. Because, at this newly found deposit, the boundary of norite and country rock slightly "bays in" instead of out they object to the gravitational theory of separation;[18] but this objection is really uncalled for. From their own account it is evident that the ore occurs at a *low* point in the edge of the basin and the slight inward bend of the country rock is clearly due to faulting. This conforms to the rule, since gravity must of course pull downward and not outward. Wherever there has been no faulting, however, the basin shape of the eruptive sheet implies that the ore should occur at outward bays as it really does.

In conclusion let me suggest to Messrs. Wandke and Hoffman, as well as others who have been impressed with the evidence of hydrothermal action at some of the mines, that they consider carefully the fact that most of the nickel-bearing sulphides of the region are not to be found in mines like the Creighton and Copper cliff but in pyrrhotite-norite which forms the lowest portion of the nickel eruptive. If their theory cannot account for these sulphides widely disseminated in rock that is sometimes perfectly fresh, it is evident that there has been some earlier, more fundamental process at work than that of circulating hot waters.

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[18] *Ibid.*, p. 573.

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ORIGIN OF METALLIC CONCENTRATIONS BY MAGMATION.

Sir: Mr. J. E. Spurr's address on the origin of metallic ore veins (ECONOMIC GEOLOGY, vol. XVIII., No. 7) marks a distinct advance in the study of ore deposits, collating, as it does, in precise form the ideas which have for some time been rapidly forming, and gaining ground, in the literature of economic geology. May I be permitted to discuss one or two points in his paper?

The zonal theory of ore deposition has of late years been almost universally accepted in its application to ore bodies directly related to igneous masses, the accumulated evidence being now almost overwhelming in its favour. In such ore deposits, however, the governing factor seems to be not the original normal terrestrial temperature gradient due to depth, but rather that temperature gradient within and about the igneous mass during and immediately subsequent to its crystallization. The isotherms about such an igneous mass will be the resultant of those due to the magma itself and the normal terrestrial isotherms. These isotherms will not, therefore, be parallel or concentric about the granite surface, but will be relatively close together at the crest of the igneous mass, widening laterally until they merge into the normal terrestrial isotherms at some distance laterally from the granite mass, depending upon the relative conductivity of the surrounding rocks. It will, therefore, follow as a necessary corollary that any particular ore mineral will have a greater range over which it can crystallize laterally than vertically. Minerals which, if they ascended vertically from an igneous mass, may have a range of only a few hundred feet within which to crystallise, would laterally have that range extended to perhaps a mile or more. This would account for the very considerable distances at which many minerals are found from a granitic mass, although their vertical range of deposition (perhaps the depth of the ore shoot) is relatively restricted. Carbonates and siliceous gold ores found frequently at great distances from granitic masses

seem to owe their localization to deep seated lateral migration between isotherms rather than immediate vertical movements of the ore solutions. The greater distance over which crystallization takes place, and therefore the greater time period throughout which minerals can crystallize and separate themselves from the ore solutions, will account for the simplicity of individual lodes at some distance laterally from a granitic mass as compared with the complexity of lodes in the immediate vicinity of the igneous intrusion.

It is therefore the lateral rather than the vertical movement of the solutions that is the important factor in the broad localization or lateral zonal distribution of economic ore deposits. But in any particular lode close to the crest of the granite mass it is practically the vertical component of the temperature gradient that determines the ore zones (or shoots) and it is the contraction or lowering of the isotherms that determines mineral sequence and superposition.

In the interpretation of mineral sequence in the past too little attention has been paid to the influence of each mineral, and its relative concentration in the ore solution, on the temperature of deposition of the others. The phase rule surely is universal, and ore solutions are subject to it just as are simple inorganic solutions. Each ore solution will have its own hypothetical phase diagram of crystallization, each ore mineral its "field" of crystallization, influenced by the "field" of crystallization of the other ore minerals. A mineral sequence as determined from the phase diagram of one ore solution may in the case of many minerals be quite the reverse of the sequence characteristic of another ore solution. But in general it would seem that definite *groups* of minerals retain the sequence throughout the world (*a*) tin-tungsten as high-temperature deposits, (*b*) copper iron sulphides, (*c*) zinc-lead-silver to gold ores, and (*d*) siderite and other carbonates as low-temperature deposits. It would appear that it is within the limits of each of these groups that variations in sequence occur, particularly in the sulphide group. The existence of these distinct groups is apparently a result of the small dif-

ference in temperature of deposition of the minerals *within* each group, the temperature differences *between* the groups being much more pronounced. In the case of groups (*b*) and (*c*), however, this temperature difference does not appear so striking.

The very real influence which country rock may have on ore deposits has also as yet not been fully appreciated in geological literature. Using again phase rule principles, the wall rock may not (in fact rarely would) be in stable equilibrium with the ore solution, in which case absorption will take place, just as Bowen has indicated that resorption of minerals may take place during certain stages of a crystallizing magma owing to their instability of equilibrium with the magma. Wall rock may, then, become absorbed, becoming an integral part of the ore solution itself, and so altering still further the relative temperature of crystallization of the ore minerals. Resorption of ore minerals already deposited from the ore solution may also take place. This may be the case particularly with such minerals as cassiterite, which may occasionally have two ranges of crystallization.

We owe some debt to Mr. Spurr for his frank rejection of the past belief in the primary importance of water in ore solutions. Solutions of the minerals with each other and with the accompanying mineralizers (which in order to account for all the phenomena, one must still recognize do accompany ore solutions), as well as a certain amount of water, are all that we need in deducing ore deposition on phase rule grounds. But it is difficult at once to agree to Mr. Spurr's division of ore magmas into relatively dry (aplitic type) and relatively aqueous solutions (pegmatitic type), the one forming his veindikes, the other tending to form replacement deposits. He apparently postulates a sharp line of demarcation between the two as in the case of aplites and pegmatites. These huge massive "veindikes," after all, seem relatively few as compared with those in which there is some evidence of replacement having taken place, or in which the complexity of the internal vein structure (lamination, crustification, subveining, etc.) shows that they are not due to a simple intrusion. My own personal acquaintance is with the gold reefs at Bendigo

and with lodes in other parts of Victoria, Tasmania and in Cornwall, and in these areas I have never examined any lode in which signs of replacement were entirely lacking. So abundant is the evidence of replacement, and frequently so thoroughly does it alter the whole character of the country rock that one is led almost naturally to the conclusion that replacement is perhaps the most important of all factors in the development of ore veins. Many lodes, perhaps consisting almost entirely of massive white quartz and apparently corresponding exactly with Spurr's vein-dikes (*e.g.,* many of the tin-copper lodes of Cornwall and the gold reefs of Bendigo), have on careful examination been shown to be mainly a result of replacement. Replacement has gone to its end point in which all original structure is lost. Clean cut walls of country rock are not positive evidence against replacement. I have seen many cases in which the original lode channel was a comparatively narrow shear zone between two definite clean walls, perhaps a typical fault. The ore solutions have entirely replaced the "sheeted" zone, still leaving the clean cut walls, but where replacement is not complete isolated inclusions of country rock may remain. The complexity of these lodes may even arise from the varied manner in which different bands of the "sheeted" zone have been replaced. The angular character of fragments is also no criterion against replacement, nor does replacement frequently seem to attack corners or edges more than other parts.

The formation of lodes (as distinct from dikes) seems such a relatively gradual process, taking place over a considerable period of time, during which all the complexities of banding and sub-veining take place, that I find it difficult to picture the sudden intrusion of an ore mass under tremendous pressure. The force exerted by minerals during crystallization seems also to be a definite factor in the growth of veins (not the "force of crystallization" of Spurr), although perhaps not one of absolute importance. The position, shape and occurrence of many sub-veins within a lode, the position, the orientation and peculiar manner in which near sides of neighbouring fragments fit into each other,

and all the phenomena so well illustrated by Taber, Stillwell (in the Bendigo gold-quartz reefs) and others, all are definite evidence—no theory of mere intrusion under pressure could explain them. The banding and ringed structure quoted by Spurr is just as aptly, perhaps better, explained by growth by force during crystallization of vein minerals separating from an ore solution as the isotherms become successively lowered.

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In any particular lode, it would appear that not one factor, but a number contribute to its formation and enlargement. The earlier ore solutions intruded, as they may be, under pressure, forced apart certain openings forming a more easy channel for the travel of the later ore solutions. But replacement, accompanied by growth due to the force exerted by the mineral while separating out from the solution, continued the enlargement, and these were, I believe, the main factors in producing lodes of their present width and extent. As all three influences can almost invariably be found in one and the same lode, Mr. Spurr's marked division of lodes into aplitic and pegmatitic types has, apparently, no clear bearing of truth or possibility. If it were possible to have two such distinct types, then the evidence of lodes would (accepting Mr. Spurr's criteria for recognizing his two types) suggest that there is a gradual transition from one to the other—from aplitic to pegmatitic types, the ore magma becoming higher in water as other minerals crystallized out. That is, the earlier lode solutions would tend to produce an aplitic, massive (or dry) type of vein, the later solutions would be largely responsible for the replacement of country and earlier vein rock. Mr. Spurr quotes instances of his pegmatitic type replacing limestone, and of his aplitic type showing no signs of such replacement, using this varied behaviour on limestone country rock as evidence of the existence of the two types. This varied behaviour may however be better explained by the phase rule—the extent to which the country rock is in equilibrium with the varied ore solutions. In fact, the whole crystallization of ore minerals seems bound up with the phase rule laws—the stability of ore solutions, the equilibria between mineral and ore solutions and be-

tween country rock and ore solution, the effects of absorption of country and resorption of earlier minerals on the crystallization of minerals still in solution—all these may play their part in the crystallization of the minerals of an ore body, but as yet little or no real attention has been given to them in geological literature. The phase rule is of as much importance to the economic geologist in the interpretation of the phenomena of ore deposits as it is to the chemist in his work on polyphase solutions.

Finally, one cannot help but feel indebted to Mr. Spurr's outspoken protest against the belief that idiomorphic form is a definite criterion on which to base relative ages of minerals. Only too often has this criterion, in my own experience, proved unreliable, the relative ease of migration, replacement and growth seeming to be rather the determining factors. Indeed, it appears to me that only on two factors taken together can any deduction be based—veining and replacement. Even veining alone I have often found unreliable, for frequently a narrow vein may cut through country rock which has been later replaced by quartz, for example, leaving the original vein almost intact as a "ghost" vein.

J. A. DUNN.

GEOLOGICAL SURVEY OF INDIA.

STUDY OF POLISHED SURFACES.

Sir: I read with interest Dr. Sampson's communication on the determination of anisotropism in polished metallic minerals and the use of the Wright biquartz-wedge-plate.[1] As pointed out by Sampson, Schneiderhöhn[2] realized the possibilities of using reflected light to advantage, but does not employ the biquartz-wedge-plate. Dr. Sampson, however, points out the possibility of not only detecting anisotropism, but of making a quantitative determination of the rotation of the plane of polarization when the wedge is employed. He refers especially to manganite be-

[1] This journal, vol. 18, pp. 775–777, 1923.

[2] Anleitung zur Mikroscopischen Bestimmung und Untersuchtung von Erzen, Berlin, 1922.

cause it is strongly anisotropic and takes such a good polish as to cause a minimum of disturbing effects.

In this note the writer also wishes to recommend the use of the method suggested by Sampson, and to emphasize its value for polished surfaces of ores in which there are transparent colored minerals and fine aggregates of opaque minerals that show but slight anisotropism between crossed nicols. In many cases the mineral is but very little brighter in the position of greatest rotation of the plane of polarization than it is at extinction and doubt arises as to whether it is isotropic. The biquartz-wedge-plate accentuates this change which proves to be of diagnostic value. In other cases various color effects are produced that aid in determining the mineral species. Several examples may be cited.

Hematite and Ilmenite.—In making a study of the magnetite ores of the Cuyuna range[3] it was necessary to work with minute intergrowths of such opaque minerals as magnetite, hematite, limonite, manganite, psilomelane, pyrolusite, ilmenite and rutile, and numerous colored transparent amphiboles and pyroxenes together with more unusual minerals such as stilpnomelane and hisingerite. In some of the titaniferous magnetites, ilmenite and hematite occur as intimate intergrowths with magnetite. In the determinative tables for studying polished surfaces of opaque ores[4] no satisfactory method is given for distinguishing hematite from ilmenite. In reflected polarized light both are slightly anisotropic between crossed nicols and can not be distinguished. With the insertion of the biquartz-wedge-plate, however, hematite passes from a pale bluish gray to a bright blue when the stage is rotated; whereas, ilmenite passes from a light gray to a dark and slightly bluish gray when rotated with the wedge in the same position. Schneiderhöhn states that ilmenite can be distinguished

[3] The details of the paragenesis of these ores, together with their reactions and those of other opaque minerals to reflected polarized light will appear in a later paper. For the paragenesis of the manganese minerals in the manganiferous ores of the Cuyuna range see: Thiel, Geo. A., "The Manganese Minerals, their Identification and Paragenesis," ECON. GEOL., vol. 19, p. 107, 1924.

[4] Murdock, J., "Microscopic Determination of Opaque Minerals," John Wiley & Son, Inc., New York; Davy, W. M., and Farnham, C. M., Microscopic Examination of Ore Minerals," McGraw-Hill Co., New York.

from hematite by its twinning bands and by its darker rose-gray color in reflected light. However, many specimens of Cuyuna range hematite show twinning as conspicuously developed as that of ilmenite. This is especially true of the micaceous specular hematite found in quartz-hematite-manganite veins.

Colored Transparent Minerals.—With reflected polarized light a more comprehensive study can be made of the relations of opaque and transparent minerals. When reflected light is not polarized all of the transparent minerals appear dark gray on polished surfaces, but between crossed nicols without the biquartz-wedge-plate, all of these dark colored minerals show characteristic internal reflections and the outlines of the grains are clearly visible. Micaceous minerals such as biotite, chlorite, and stilpnomelane and basal sections of hornblende appear nearly isotropic, even when the biquartz-wedge is inserted. Of the few varieties of tourmaline, staurolite, and titanite examined, all are strongly anisotropic with the biquartz-wedge-plate. Other varities may also show diagnostic characters. Quartz, colorless carbonates and other colorless minerals remain light grayish white between crossed nicols. Thus, in a thinly laminated slate such as the Deerwood iron formation, cherty bands can readily be distinguished from amphibole and micaceous bands in polished surface, and where the intergrowth is not too fine-grained, the relations of the transparent minerals can be established to a considerable extent without thin sections of the rock. By using the etching solutions suggested by Schneiderhöhn a still more accurate determination is possible.

All of the distinctions mentioned have proved so clear as to recommend heartily the use of Wright's biquartz-wedge-plate as a means for the identification of minerals studied by reflected polarized light.

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REVIEWS

The Evolution of Ore Deposits from Igneous Magmas. By W. H. Goodchild. *Mining Magazine*, Vol. *18*, pp. 20–29, 75–82, 131–141, 186–194, 240–249, 296–306; *19*, 21–32, 78–88, 135–144, 188–199. Jan.–Oct., 1918. Total as privately reprinted, 99 pp. Also in briefer form under the title: **The Genesis of Igneous Ore Deposits**, in *Trans. Institution of Mining and Metallurgy* (London), Vol. *28*, 274–285, 285–320 (discussion), 1919. Originally in Bulls. 177, 178, 179, 180, and 182, 1919.

The Genesis of Igneous Ore Deposits. By J. Morrow Campbell. *Trans. Inst. Mining and Metallurgy* (London), Vol. *30*, 3–27, 27–106 (discussion), 1921. Originally in Bulls. 193, 194, 195, and 200, 1920–1921.

These papers on the theory of ore deposits, with their accompanying discussions, seem to be so well representative of recent lines of thought among British mining geologists that a brief review of the principal features of the theories, from the point of view of the chemist, has been requested.

The guiding principles of Goodchild's theory as a whole are thus stated in the author's summary: "To put the whole matter in a single sentence, the formation of ore deposits from rock magmas is to be primarily ascribed to the hydrogenation of the silicate melts, while the great coordinating law which so greatly facilitates the interpretation of the phenomena is that known as the Le Chatelier Law."

The sense in which the author uses the word "hydrogenation" is evidently different from the meaning generally assigned to it by the chemist. To the organic chemist, particularly, "hydrogenation" means the addition of hydrogen to the molecule of an unsaturated compound. No such chemical reaction is in mind here. The meaning is rather the mixing and dissolving of hydrogen in silicate melts. Both the true solution of hydrogen, and the intimate mixture of gas with solid or liquid particles sometimes observed when very finely divided gas-bearing materials are heated, seem to be in mind.

With the hydrogen goes more or less oxygen. The presence of the oxides of iron in practically all natural silicate rocks and magmas provides the elasticity for the "more or less." Hydrogen, water, and the free or combined oxides of iron are assumed to be in a state of equilibrium, the quantitative proportions depending upon the temperature, pressure, and total composition.

So much for the silicate magma. Accompanying it at certain stages is a sulphide magma, which likewise contains hydrogen and iron, and in which the place of H_2O is taken by the analogous compound H_2S.

In his consideration of the chemistry of these two magmas the author is guided by the known facts of metallurgy and particularly of matte smelting, a reservoir of fact from which, in the author's opinion, the geologist and petrologist have drawn all too sparingly. At the same time he urges (with the full approval of the reviewer) that no final conclusions can be drawn from the study of thin sections, polished surfaces, or powders, unless these be studied in the light of chemical and thermal experiments in the laboratory.

The two magmas just described, existing in contact, constantly interacting, possessing iron and hydrogen as elements common to both, set the stage for the processes of sulphide ore deposition and the differentiation of the silicate magma, with all the accompanying phenomena of igneous metamorphism. With the stage thus set, natural loss or gain of heat and rise or fall of pressure supply the plot, and the Le Chatelier principle—that any external influence always calls forth an internal change which increases the resistance of the system to that influence—prompts the lines for the acts which follow.

The above is a brief description of the picture which the fundamental part of Mr. Goodchild's article presents to the reviewer, assuming that the reviewer has not rounded it out too much by reading into it things that the author did not intend to convey.

It is a well-constructed foundation for a theory, and no objections can be raised to its physics or chemistry so far as general principles are concerned. It puts into definite form for discussion what the chemists have been urging for some time, namely, that it is an unnecessary and hampering restriction to try to describe a magma in terms of compounds which are not known to be stable under the conditions postulated. SiO_2, Al_2O_3, MgO, and several other such oxides are probably quite stable under magmatic conditions and may be handled as "components" just as if they were undecomposable chemical elements. Not so with H_2O, FeS, Fe_2O_3, and the like. Here the components are H, Fe, O, and S, a quartet comprising 15 chemical systems of 1, 2, 3, or 4 components, and a correspondingly greater number of compounds and solutions. The properties of H_2O under atmospheric conditions would better be forgotten in dealing with these systems containing Fe and S under magmatic conditions. The relatively large amounts of elemental hydrogen and sulphur which accompany the water given off from the boiling lava of Kilauea emphasize this view.

Obviously, the next step in following up this promising start is to get specific physico-chemical data on the systems concerned. On the dry

undissociating silicates, the fundamental systems of the silicate magma, we have a considerable amount of reliable and thorough information. We are just beginning to get a correspondingly good body of information on silicate systems containing water alone as an additional undissociating component. On systems of the sulphides alone at high temperatures we have also a good start. But on those systems which may contain H, O, S, and their compounds as dissolvable and releasable gases our information is but fragmentary, as it is likewise on systems in which the compounds of iron are in equilibrium with one or more of these three elements, and in which, accordingly, H_2O cannot be treated as an undissociating component.

To return now to Mr. Goodchild's paper. He makes little use of the fundamental silicate and silicate-water data referred to above. He depends rather upon metallurgical data, as already noted, and also falls back upon the geological field data in particular cases. In these two subjects he is much more familiar with the detailed evidence than is the reviewer, who will therefore not attempt a particularized discussion.

From the physical chemist's point of view, however, the sequel of the author's promising start is disappointing. The author is evidently not thoroughly familiar with the thermodynamic principles which he uses. That unfortunate expression, " free energy," which seems to mean something different to each writer who uses it, crops out again here with no well-defined meaning whatever. Le Chatelier's principle is in at least one instance,—that of the chemical change produced by increase of pressure,—used to support a conclusion to which it is diametrically opposed. One class of data of which the author has made abundant use, namely the volume changes accompanying reactions which are conceivable or probable in the magmas, contains such a mixture of very good and very dubious experimental data that it is difficult to tell which of the conclusions are really reliable; certainly one of those drawn by the author, that rock magmas expand on consolidation, is directly negatived by experimental data obtained by the reviewer on a typical diabase, in which there is a contraction of 11 per cent. on crystallization.[1]

Overlooking for the moment these and other possibly unfavorable criticisms on the physics and chemistry of the paper, the reader will find a number of penetrating and suggestive hypotheses which make the paper as a whole well worth his study. This is particularly the case in the

[1] This is not to say that an expansion may not have taken place at some stage in the course of the crystallization process, to be neutralized by a greater contraction at some other stage. There is so much geological evidence of expansion that the question is not whether reactions involving expansion have occurred, but only where and why they have occurred.

discussion of those types of ore deposits, such as Sudbury and Insizwa, with which the author is directly familiar.

After all, when we consider that the Earth contains a considerable number of chemical elements, each of which behaves differently from all the rest, a complete theory of magmatic differentiation, ore deposits, and igneous metamorphism all in 100 pages, though perhaps not impossible, is too much to expect from our present fragmentary knowledge of chemistry. The author is to be commended for his courage in tackling so comprehensive a problem.

Campbell's theory covers a much wider range in time, but a relatively narrower range in subject matter, than Goodchild's. Campbell's paper may be considered in two parts, the first devoted to the evolution of present-day rocks and magmas from the period when the Earth was a molten globe, and the second, to the separation and deposition of the rarer constituents of the magma as ores. An essential premise of the first part is that the original magma was dry and only took up water as cooling progressed. This is not in agreement with the results of chemical experiment, which indicate that it is harder to take all the water out of a silicate than it is to put some in. The theory as a whole, while interesting to read and speculate upon, cannot be tied down very closely to experiment or observation; its deductions belong rather in the class of things that are possible than in the class of things that are probable.

The main argument of the second part, if the reviewer may be permitted to state it in his own terms, runs somewhat as follows. Certain features of ore deposits are recognized as common to such deposits in many localities and under a great variety of conditions; this indicates some common medium for the transport of such ores; the only media common to all are water and silica. The author thus develops his hypothesis that "silicic acids," produced by the "chemical combination" of silica and water, dissolve and carry the ore minerals, adding the further hypothesis that their deposition is controlled mainly by change of temperature and secondarily by change of pressure.

Now it is certainly true that natural water, which comes very near being the universal solvent sought by the alchemical philosophers, will take up silica and render it invisible, depositing it later as quartz; and water will do this above its own critical temperature. You may call this "true solution" or "colloidal solution" or "chemical combination" or what you like, the experimental facts stated are the same. To be sure, no one has yet succeeded in filling a large space solidly with quartz by such a method, but it has been done innumerable times by Nature, and we could no doubt learn in a few months how to do it, if learning how were, for example, a matter of great financial importance to some large manufacturing concern with a well-equipped research laboratory.

The next questions in logical order, questions raised by several of those who discussed the paper, are these: (1) Is silica necessary to the transportation of the ores, or is it only incidental, leaving water as the necessary and sufficient carrier? (2) Is there some other constituent, besides water, which is so nearly universal as to require consideration? These questions, in the reviewer's opinion, can be answered only by the combined contributions of field geology, laboratory experiment, and field chemistry,—meaning by "field chemistry" the chemical study of materials collected by the chemist himself in full view of their natural associations. In his capacity as geochemist he has as much need of keeping in touch with the field relations as has the geologist, and he cannot progress far with material bought from a dealer, found in a collection, or handed to him by the geologist. It is the lack of such necessary geochemical data, rather than a lack of strictly chemical or geological information, that prevents our making a satisfactory estimate of the merits of such hypotheses as Campbell's.

In several of the discussions mention was made of a proposal, now unfortunately slumbering in a government committee, to establish in England a physico-chemical-petrological research laboratory. If the mining industry in general realized as vividly as the authors and most of the discussers of these papers how valuable such a laboratory could be to the industry, the small beginnings of such work in America would soon be receiving vigorous and valuable additions from our British colleagues.

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A Textbook of Geology, Part II., Historical Geology. By CHARLES SCHUCHERT. Second Revised Edition. New York, John Wiley and Sons., Inc., 1924.

The new edition of "Historical Geology" by Professor Schuchert is superior to the first edition and is also more extensive. Many of the chapters have been almost completely rewritten and several of them are essentially new. The book is better adapted for teaching than was the first edition, is better written, and more readable.

The story of the history of the earth is dramatically told, both from the point of view of the evolution of life and the evolution of the physical features of the surface. Individual chapters, or parts of chapters, are devoted to the evolution of plants, fish, dinosaurs, horses, camels, elephants, etc., the various groups of organisms being considered in the order of their appearance in time. Sixteen chapters are devoted to the consideration of organisms and, in addition, there are three chapters which

discuss fossils, the general subject of organic evolution and the characteristics of organisms. The evolution of the physical features of the earth is treated very largely from the point of view of the North American continent, from which are drawn most of the illustrations and to which most of the applications are made.

The book contains four chapters the subject matter of which would seem to belong more properly to Part I., or Physical Geology. Two of these chapters, numbers V. and VI., relate to continents, oceans, and seas; Chapter XX. treats of petroleum and natural gas and chapter XXIX. of coal.

The division of earth history into eras, periods, etc., is given in a "geologic time table" which differs somewhat from that of the first edition. In particular, the table is less positive with respect to the Pre-Cambrian, the Ozarkian is removed from the base of the Ordovician and made the uppermost division of the Cambrian, the term Champlainian is applied to the period generally known as the Ordovician, and the Comanchean and Cretaceous periods of the first edition are united under the latter name. Some of the classification of the geologic sequence is uncertain, and the text would be improved were this clearly and definitely stated. This is particularly essential with respect to the lesser known portions of the geologic sequence and geologic time. In the Pre-Cambrian the periods and systems are little known and most, if not all, of the subdivisions which have been proposed must be considered merely tentative and such probably is also true of other portions of the geologic column. This fact should receive constant repetition, particularly in an elementary work, so that students do not assume that the divisions are fixed and determined. The substitution of Champlainian for Ordovician is not likely to meet with the approval of a large number of geologists, but the union of all the Cretaceous strata into one system seems a move in the right direction.

Rather frequent references are made to what particular geologists have said, found, or thought. As the book is primarily intended for beginning students in geology to whom these names have no meaning and by whom they are essentially never remembered, it would seem that nothing is gained by their introduction and that their omission would have been desirable.

The illustrations are well selected and ample. Particularly noteworthy are the author's paleogeographic maps and Lobeck's restorations of the physiography of some of the ancient surfaces. These are speculative, and this should have been repeatedly stated; but they serve to stimulate the imagination and to fix the conception that "nothing is constant but change." Photographs of the great founders of geology are given in appropriate connections.

Considering the work as a whole, in the reviewer's opinion it is one of the most readable and interesting works on historical geology which has appeared during the past twenty-five years and from the point of view of holding the reader's attention it vies with the "Elements" of LeConte. As one elementary student in the reviewer's classes stated "It is a book which one studies without realizing it."

W. H. TWENHOFEL.

SCIENTIFIC NOTES AND NEWS

Josiah Edward Spurr has been reappointed a member of the Advisory Committee of the Natural Resources Production Department of the Chamber of Commerce of the United States of America.

Alfred C. Lane has returned to Boston from a summer in Europe.

N. W. Bass, of the U. S. Geological Survey, has been at Syracuse, Kansas, where he mapped geologic structure.

Allan B. Calhoun, superintendent of the Burma Mines, Ltd., Burma, India, has returned to Burma after visiting his home in Minneapolis.

Robert Harvie, formerly with the Geological Survey of Canada, has commenced practice as consulting mining geologist.

A. A. Pegan is acting professor of geology at the University of Virginia.

T. K. Scott has resigned his position as chief engineer for the Miami Copper Company.

Guy C. Riddell of New York City has been appointed chief of the Minerals Division of the Bureau of Foreign and Domestic Commerce, Washington, D. C.

Llewellyn H. Wilkins, formerly with the Mexamerican Oil Company, Ltd., has opened an office as consulting engineer and geologist at 46 Fish Street Hill, London.

N. H. Darton is in Mexico on leave of absence for two months, to determine the age of the pre-Maya remains and temple near Mexico City for the National Geographic Society.

R. S. Knappen, assistant professor of economic geology at the University of Kansas, has been visiting the principal mining districts in Nevada.

Edwin E. Chase, associated with William A. Perkins, graduate geologist of Brown University, spent the month of July on geological examination work in Northwestern Colorado, with headquarters at Steamboat Springs.

George Hanson, of the Canadian Geological Survey, and three assistants, have been making a survey of the properties contiguous to the Grank Trunk Pacific Ry. between Prince Rupert and Telkawa.

W. A. Tarr of the Geology Department of the University of Missouri, left the middle of August for a year's study and travel in Europe. In addition to visiting the important mineral deposits he will continue his

studies of chert, stylolites and related features of sedimentary rocks. Part of the year will be spent in the laboratories of Dr. R. H. Rastall at Cambridge University.

E. Russell Lloyd, formerly associated with Max Ball in the Marine Oil Company, has opened offices at 1104 First National Bank Building, Denver, Colorado, as consulting geologist.

G. C. Gester, chief geologist of foreign department of the Standard Oil Company of California, is in South America.

Alex H. Smith has been appointed manager for the British Canadian Mines, Ltd., at the Foley mine, Mine Centre, Ontario.

H. I. Jensen, of Brisbane, Queensland, Australia, has been examining oil prospecting country in South Australia.

Edwin B. Hopkins has returned from consulting work in Venezuela, South America, and has taken up his duties in his New York Office.

C. N. Gould has been appointed director of the Oklahoma Geological Survey.

M. R. Campbell and W. T. Thom have been doing geologic work for the U. S. Geological Survey in the Lykens Valley anthracite field.

R. E. Allen, consulting geologist, has accepted the position of director of exploration and development for the Landers Oil Company, Ltd.

E. M. Spreker, formerly of the U. S. Geological Survey, has been appointed assistant professor of geology at Ohio State University.

Alex F. Serebrovsky, director of oil operations for the Russian Government in Baku, is making a tour of all of the oil fields of this country and visiting some of the largest refineries.

J. J. Forbes, the district engineer of the U. S. Bureau of Mines at Birmingham, Alabama, is in Washington acting as engineer in charge of the division of mining research, in the absence of M. Van Siclen, who is in Oklahoma.

George H. Chadwick is stationed at San Antonio, Texas, as geologist to the Empire Gas & Fuel Company, with offices at 305 Maverick Building.

Robert Hughes, formerly with the Inspiration Consolidated Copper Company, has been appointed chief mining engineer of the Miami Copper Company plant at Miami, Arizona.

H. Charlton Dod, who is in charge of the operations of the South Australian Oil Wells Company, has written to the Australian press controverting the opinion of E. M. di Villa, a visiting geologist, that the prospects for oil are unfavorable in Victoria and South Australia.

F. L. Ransome was a recent visitor in Washington.

W. G. Miller gave a course of three lectures on "The Pre-Cambrian with special reference to Ontario" at the University of London during the summer.

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T. S. Lovering of the University of Minnesota has been appointed an instructor in the Department of Geology in the University of Arizona.

A. H. Brooks, chief of the Alaska section of the U. S. Geological Survey, has been in Alaska visiting the different field parties of the Survey.

Heath M. Robinson, petroleum geologist, recently resigned from the staff of F. Julius Fohs and has opened an office at 304 American Exchange National Bank Building, Dallas, Texas. Prior to his connection with Mr. Fohs he was a member of the U. S. Geological Survey.

John T. Reid has been in his office in Lovelock, Nevada, for the summer. He will go to New York about November 1 and will remain there for the winter.

A. F. Buddington of the U. S. Geological Survey has been studying the geology of the west coast of Prince of Wales Island and north of Wrangell, Alaska.

Eggleston Smith announces the opening of an office in New York in connection with his inventions in well drilling apparatus with special reference to the recovery of rock cores.

J. T. Pardee of the U. S. Geological Survey has been in Drummond, Montana, studying the phosphate deposits near Phillipsburg.

E. S. Larsen of Harvard University has been investigating the geologic conditions controlling the formation and distribution of pegmatites and their associated rare minerals in southern California in the vicinity of Pala and Mesa Grande.

D. F. Hewett left the latter part of August for Las Vegas, Nevada, to begin work on the areal geology and economic resources of the Ivanpah quadrangle, Nevada-California, for the U. S. Geological Survey.

W. T. Schaller has been in California collecting mineralogical specimens for study for the U. S. Geological Survey, with special reference to the tourmalines and pegmatites of southern California.

J. D. Northrop has been at work on coal, oil, and phosphate cases in the region between Evanston and Kemmerer, Wyoming, for the U. S. Geological Survey.

At the bi-weekly luncheon held at the Cafe Lousian, Tampico, Mexico, on July 2, Dr. J. J. Galloway spoke on the use of foraminifera in geologic age determinations. There were present: P. H. Bohart, A. H. Armstrong, H. G. Shelton and S. A. Grogan of the Mexican Gulf Company; A. W. Noble, Paul Weaver, C. S. Adams, G. F. Kaufman, and W. S. Adkins of the Aguila-Corona Company; J. J. Galloway, S. R. Saye, M. P. White, and S. W. Lowman of the International Petroleum Company; H. F. Nash, D. D. Sparks, and Theodore Chapin of the Empire Oil & Gas Company; R. G. Reese of the Mexican-Sinclair; W. A. Baker of the Transcontinental Petroleum; and Walt M. Small, J. B. Dorr, and E. B. Stiles of the Agwi Company.

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